ELECTRORHEOLOGICAL FLUIDS: FUNDAMENTALS AND ENGINEERING APPLICATIONS

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By

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Department of Mechanical Engineering

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Dedication

To Jianguo

and

a liberal democratic and rich China

STATEMENT OF ORIGINALITY

This thesis is submitted for the Degree of Doctor of Philosophy in the Faculty of Engineering at the University of Liverpool.

The research reported herein was carried out, unless otherwise indicated, by the author in the Department of Mechanical Engineering at the University of Liverpool between October, 1987 and September, 1990.

No part of this thesis has been submitted for a degree to any other university or educational institution.

September, 1990 Xin Ming Wu

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ABSTRACT

The research reported in this thesis is concentrated on the theoretical analysis of electrorheological systems and on the practical design and development of devices using ER fluids.

The theoretical analysis on how different factors influence the ER effect is based on two ER circuit models. It is shown that an increase in the frequency of the applied field leads to the weakening of the ER effect. An increase in the resistance of the ER fluid itself and the decrease in the resistance of the circuit of an ER system generally leads to the strengthening of the ER effect.

Some new application concepts using the ER effect are developed. One is the combination of an ER coupling with a gear train to form an ER mechanical power transmission device which can run at a higher efficiency than the ER coupling itself. The other concept is a universal ER directional control valve which is formed by arranging eight unit ER valves together to achieve different functions. The universal valve can be used to replace any conventional directional control valves except the check valve.

Principle and design aspects of ER power transmission devices are discussed and experimental results show that a single plate ER brake can transmit a brake torque from 2 Nm to 4.5 Nm when the applied voltage increases from 0 to 7 kV. An ER cooling fan drive proved to be capable of providing a variable fan speed over a reasonable range by the control of applied voltage. A multiplate ER drive shaft was shown capable of achieving a variable speed drive, a constant torque drive and a constant output speed drive by the control of voltage. Transmitted torque generally was seen to increase

parabolically with applied voltage Although the increase in the temperature was found to lead the decrease in the pure viscous effect of the ER fluid, it leads to an increase in the pure electrorheological effect.

Discussions are also presented concerning the principle of an ER damper designed to be an adaptive damping element for a suspension system. However, the experiments with the ER damper involve a single degree of freedom vibration test station. Results show that an ER damper is equivalent to a number of conventional dampers with different damping coefficients. It is shown that an ER damper with a thin ER fluid basically behaves in the manner of viscous damping.

Finally, suggestions are given to further research.

NOTATION

Chapter 2

A	area
C	capacitance
d	gap between electrodes
E	electric field strength
E_{dc}^{∞}	steady state DC field strength
E_{ac}^{∞}	steady state AC field strength
$\overline{E}_{ac}^{\infty}$	mean value of steady state AC field strength
F	force
i	current
i_{dc}^{∞}	steady state DC current
i_{ac}^{∞}	steady state AC current
$\bar{i}_{ac}^{\infty}$	mean value of steady state AC current
K	constant
P	electric power
P_{dc}^{∞}	steady state DC power
P_{ac}^{∞}	steady state AC power
$\overline{P}_{ac}^{\infty}$	mean value of steady state AC power
P_t	total power needed to control an ER system .
P_t^{∞}	total steady state power needed to control an ER system
$\overline{P}_{ac}^{\infty}$	mean value of total steady state power needed to control an ER system
q	electric charge

Q	maximum electric charge
q^{∞}	steady state electric charge
r	resistance of an ER fluid
R	resistance of the circuit of an ER system
t	time
T	temperature
v	voltage
V_0	amplitude of sinusoidal voltage
α, β, γ	phase angle
ω	angular frequency
ε	permittivity
μ	dynamic viscosity of ER fluid
μ_0	original dynamic viscosity of ER fluid
$\mathcal{E}$	electromotive force

Chapter 3

A	connection parameter of a planetary gear train
C	constant
e_1, e_2, e_3, e_4	parameters defined by the arrangement of planetary gear with ER coupling
F	force
h	gap between electrodes
i_{21}	ratio of output speed to input speed
L	length
m	number of working surfaces
n_1, n_2	input and output rotational speeds

N	power
N_1, N_2	input and output power
N_s	slipping power dissipated as heat
p	pressure
r	effective radius, radial direction
r_1, r_2	inner and outer radius
t	time
T	torque
T_1, T_2	input and output torque
T_v, T_e	pure viscous and pure electrorheological torque
u,v,w	velocity in the direction of x, y and z, respectively.
x,y,z	co-ordinate directions
α	structure parameter of planetary gear train which is the ratio of the teeth number of the annulus gear to that of the sun gear
τ	shear stress
μ	dynamic viscosity
θ	angle in cylindrical co-ordinate system
ω_1, ω_2	input and output angular speeds
$\Delta\omega$	difference between output and input angular speed

Chapter 4

A	connection parameter of a planetary gear train
e_1, e_2, e_3, e_4	parameters defined by the arrangement of planetary gear with ER coupling
i_1	speed ratio of ER coupling

i_2	speed ratio of gear train
i_{21}	ratio of output speed to input speed
i_{pa}	speed ratio of passive part to active part of the ER coupling
n_1, n_2	input and output rotational speeds
n_3	rotational speed of the third element of the planetary gear
n_a, n_p	input and output rotational speeds of the active and passive part of the ER coupling
T_1, T_2	input and output torque
T_a, T_p	torque of active and passive parts
x,y,z	co-ordinate directions
α	structure parameter of planetary gear train (ratio of the teeth number on the annulus gear to that of the sun gear)

Chapter 5

A_1, A_2	cylinder surface areas
c	damping coefficient
F	magnitude of exciting force
F_{ev}	viscous shear force
k	spring constant
l	length of shear surface in ER damper
m	mass
n	number of shear surfaces
r	radius of shear surface
r_1, r_2	inner and outer radius

X	displacement amplitude
x, u	displacement of mass and foundation
$\dot{x}$, $\dot{u}$	velocity of mass and foundation
$\ddot{x}$, $\ddot{u}$	acceleration of mass and foundation
x_{st}	static deflection
τ	shaer stress
μ	dynamic viscosity of ER fluid
ω	angular frequency of exciting force
ω_n	natural frequency

Chapter 6

b	width
F_o	force opposing motion of ER fluid
F_c	force causing motion of ER fluid
h	height
L	length
p	pressure
$\frac{dv}{dy}$	velocity gradient

Chapter 7

A	area
C	constant
l	length
Q	energy of heat
r_1, r_2	inner and outer radii

t	temperature
t_1, t_2	temperatures at inner and outer surfaces
λ	thermal conductivity
δ	thickness between inner and outer surfaces

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Definition of the Electrorheological Effect

When a suitable dielectric liquid is contaminated with semi-conducting polymer particles and the resulting mixture is stressed by an electric field, then the apparent viscosity of the fluid exhibits an increase over the original viscosity. This increase continues as the electric field increases until eventually a breakdown point is reached. The process is reversible, i.e., when the electric field decreases, the apparent viscosity also decreases until the zero-field viscosity is reached. Liquid suspensions of this kind are called electrorheological fluids. The term 'electrorheological' (ER) is often confused with 'electroviscous' (EV). Electroviscous fluids are those pure liquids which exhibit an increase in viscosity under no externally applied electric field [1].

Although the electric field applied across the ER fluid may be relatively high (between 2 and 5kV/mm), the current passing through the fluid is unlikely to exceed a few milliamps because of the dielectric property of the fluid. Thus the power needed for the above effect is relatively small, typically of the order of a few watts. The response time of the process is reported to be of the order of milliseconds [2].

1.2 Historical Background of Electrorheological Fluids

1.2.1 Fluids in Engineering Applications

The earliest fluid in engineering applications was probably water [3]. The development of mineral oils made a boost in hydraulic control and power transmission because of their improved lubrication properties. Hydrostatic transmission has been in engineering application for hundreds of years and hydrodynamic transmission, i.e., fluid coupling and torque converter, were seen early this century in the shipping industry [4]. At the end of the 1950's and the early 1960's, a new continuously variable fluid power transmission, the so-called hydroviscous drive (HVD) was developed for power control and transmission [5] This is probably the earliest example in which viscous shear stress (or friction) was used for the purpose of power transmission. Principally, ER devices also depend on viscous shear stresses to transmit and brake power. However ER viscous shear stress not only varies with shear rate but also with the electric field applied across the fluid.

1.2.2 The Discovery of the ER Phenomenon and pioneering Research Work

The first investigation into the viscosity of dielectric liquids under electrostatic stress was probably by Konig [6] in 1885. However, no discernible change in viscosity was found. In 1896, Duff [7] carried out a series of experiments to study the viscosity of polarised dielectrics. Figure 1.1 shows Duff's apparatus which was used to measure the variations in the viscosity of liquids with an applied electric field. Referring to Figure 1.1, a tube, AD, was filled with the liquid to be tested and two condenser plates were placed opposite the middle part of the tube. A small drop of mercury or an imitation

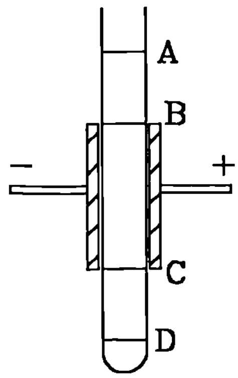

Figure 1.1 Duff's electroviscometer

pearl sphere was allowed to descend through the tube, and it was assumed that as the viscosity of the liquid increased, the descent time of the sphere through a given distance in the medium also increased. Glycerin was the first liquid tested, but failed to exhibit a regular variation in viscosity. An irregular variation or even a decrease of viscosity was found in heavy paraffin oil. Castor oil was found to suffer an increase of viscosity of up to 0.53% under an electrostatic stress of 2.7 kV/mm. While such results are of scientific interest, they are unlikely to convince anyone of potential engineering applications.

Following these early investigations, little research into this area was reported until the 1930's. In 1939, Andrade and Dodd [8] described their experimental investigation into the effect of an electric field on the viscosity of liquids. The results indicated that under a transverse electric field, nonpolar liquids showed no measurable change in viscosity even for a field of 4.0kV/mm. However, viscosity increases of up to 115% were achieved with polar liquids. The extent of the viscosity change decraesed with decreasing conductivity of the liquids.

Meanwhile, Russian scientists Sokolow and Sossinski [9] pointed out that they had performed similar work in 1935. It was shown that the increase of viscosity (up to 100%) was due to the passage of an electric current through the liquid. Increased viscosity was also observed in non-polar liquids which were artificially contaminated with a few drops of acetone. They proposed that the effect was a purely hydrodynamic phenomenon due to the convection of the non-homogeneous liquid in the electric field. On the other hand, Andrade and Dodd [10] pointed out that Sokolow and Sossinski's experimental method was not as precise as theirs and that hydrodynamic convection would not explain either the saturation at large fields or the lack of parallelism between the current and viscosity increase.

Andrade and Dodd's work was further published in detail in 1946 [11] Figure 1.2 shows the facility that this investigation used to measure the viscosity of the electrically stressed liquids. Here the liquid tested was flowing from a viscometer through a thin gap formed by separating the electrodes which supplied a transverse electric field across the liquid. Electric current was measured at the same time. Non-polar liquids, such as carbon disulphide, carbon tetrachloride and benzene were tested first. All of these showed no apparent change in viscosity even when the electric field was greater than 2.6kV/mm. With polar liquids, acetonitrile showed a maximum viscosity enhancement of 115% and it was found that the enhancement decreased with

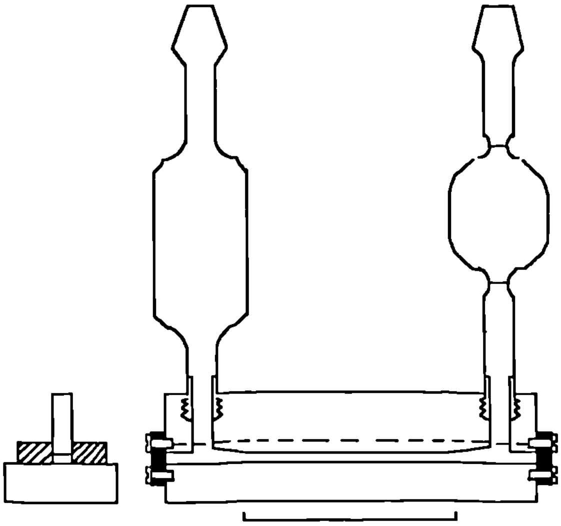

Figure 1.2 Andrade and Dodd's electroviscometer

decreasing conductivity of the liquid. This means that current passing through the liquid assists in the effective increase of viscosity. With acetone, diethylamine, ethylene dichloride, similar results were obtained. It was interesting to find that a pure diethyl ether hardly conducted at all and also showed no viscosity variation even at 3.5kV/mm. However when mixed with a little water, an apparent viscosity increase was seen. Different size gaps between the electrodes were tried and it was found that the effective viscosity decreased with increasing gap size even though the electric fields were unchanged. However, the current author does not agree with it.

The effect of an alternating electric field on the viscosity of liquids was also assessed. Results, however, indicated that the D.C. field produced the best effect, but there existed a frequency where the effect was more pronounced than at other frequencies. It was shown that there was a critical frequency after which the effect decreased rapidly. This critical frequency increased with rising temperature and was roughly inversely proportional to the size of the gap. Andrade and Dodd concluded that there were three classes of liquid:

1. Non-polar liquids, which showed no discernible viscosity effect, whether they were dry and non-conducting, or wet and conducting.

2. Polar liquids which have very low conductivity and which show no discernible viscosity effect.

3. Polar liquids which conduct, either as ordinarily termed 'pure' or on the addition of moisture, and do exhibit significant changes in viscosity.

Experiments involving successive purifications [11] indicate that if a specimen could be prepared so as not to conduct at all, there would be little or no effect. The general conclusion is, then, that for the variable viscosity effect to exist, neither conduction nor polar molecules will alone suffice, but that both must be present.

Some five years later, further more accurate measurements were made by Andrade and Dodd on the effect of high frequency fields on the increase of viscosity [12]. It was shown that non-polar benzene displayed no effect even at the highest applied fields. However, polar liquids showed a very small increase in viscosity proportional to the square of the field.

In 1954, Eisenschitz and Cole tried to explain the effect of an electric field on liquid viscosity using molecular theory [13]. They used a simplified molecular model by assuming that the molecules of the liquid interact with central forces on which the forces of a molecular dipole may be superposed. The intermolecular forces which were induced by the electric field contributed to the change in the viscosity. However, no experimental work was presented to verify this theory.

In Germany, Bjornstahl and Snellman [14,15,16] studied the influence of a transverse electric field on the viscosity of some pure liquids and colloidal dispersions of metal and sulphur in dielectric liquids. It was shown that acolotropic liquids exhibited an increase in viscosity when subjected to both DC and AC fields. However, ordinary isotropic insulating liquids showed an apparent decrease in viscosity with a DC field, which was assumed to be due to electrolysis. It should perhaps be noted the maximum field applied to the liquids was only 800V/cm. Their experimental method was openly criticised by many later investigators.

Much more convincing experimental work has been carried out by Winslow [17] in the USA since 1939. It is generally accepted that Winslow was the first investigator to describe experiments involving suspensions of particles in carrier fluids. He also first proposed a series of possible applications employing such fluids as working media. Experiments showed that certain particles suspended in low viscosity oils form an oil-occluding fibrous mass when stressed by an electric field. The fibre chains are formed in such a manner that the electrodes are mechanically linked together. It was pointed out that the effect was intrinsically reversible under the action of shear.

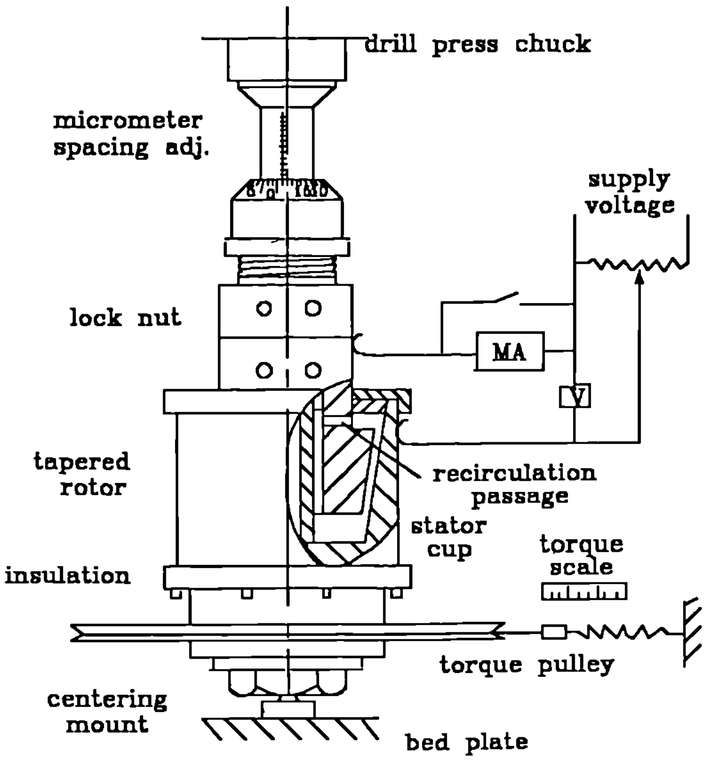

Figure 1.3: Winslow's electroviscometer

Winslow found that particles most suitable were semi-conducting solids with a high dielectric constant, such as activated silica gel powders. By means of a rotational electroviscometer shown in Figure 1.3, it was found that a concentrated suspension with particle volume exceeding 38%, and base oil viscosity below 20 cP at 25°C, could yield the best results. It was proposed that the induced shear resistance, S, is approximately a parabolic function of applied voltage, V, that is:

$$S \pm S_0 = K(V \pm V_0)^2 \tag{1.1}$$

where the supplemental potential V_0, supplemental shear resistance S_0, and constant K are determined from fluid properties. However, this equation seems not practically right.

Winslow's explanation of the ER effect is the electrically induced fibration of particles, that is, the particles could form a series of fibres which made the viscosity increase when under relative movement.

A few patents [18,19,20,21] have been filed since 1947, concerning ER power transmission clutches, ER hydraulic valves, ER shock absorbers and the compositions of a series of ER fluids. ER fluids, as defined by Winslow, were composed of at least 15% by weight of a liquid oleaginous base oil having a viscosity not greater than lubricating oil and a dielectric constant from about 2 to 5.5, and 30% to 70% by weight of fine particles, and 0.75% to 15% by weight of water as well as 5% to 15% by weight of surface active dispersing agent. Although hundreds of fluids were made, no practical applications were seen from his devices, primarily because of the low yield stresses and highly abrasive properties of the fluids.

Due to Winslow's significant contribution, the ER effect became known as the Winslow effect by many later researchers. It is clear that Winslow believed water played an important role in strengthening the semi-conducting property of ER fluids.

In 1959, Klass and Martinek started their research and a series of detailed investigations have been reported since then [22]. It appears that they first described the 'effect of an electric field on the viscosity of liquid' as an 'electroviscous effect' which is 'essentially instantaneous and reversible'. The dispersion fluid they used was a naphthenic carrier contaminated with silica particles. A large number of tests was conducted and it was found that the apparent viscosity increased with field strength, that the apparent viscosity of the dispersion decreased with shear rate, and that a higher volume fraction of particles afforded higher electroviscosity at constant field strength and shear rate. It was demonstrated that constant applied field strength at different electrode spacings had about the same effect on 'electroviscosity': this was defined as the arithmetic difference between apparent viscosity and zero-field viscosity. This, however, conflicts with Andrade and Dodd's results [11].

A model depicting the electroviscous effect was established and the mechanism was based on the induced polarisation of the double layer surrounding each particle, as shown in Figure 1.4. It was explained that 'the resulting electrostatic interaction of the distorted double layer in the medium of low dielectric constant requires the dissipation of additional energy on application of a shear stress normal to the direction of the field-induced distortion. This increased energy dissipation manifests itself as the electroviscous effect.' Obviously, Klass and Martinek would partially disagree with Winslow's model of 'formation of particle chains', insisting 'chain formation undoubtedly occurred by particle migration, but the time required (for particle migration) would be excessive when compared to the short response and relaxation times of electroviscous dispersions'. It was also pointed out that particle migration was not observed during their microscopic examination of electroviscous dispersions under strong uniform AC and DC fields and zero shear. It is interesting to note that they observed that an incremental effect of the applied field on electroviscosity is greater at higher temperatures.

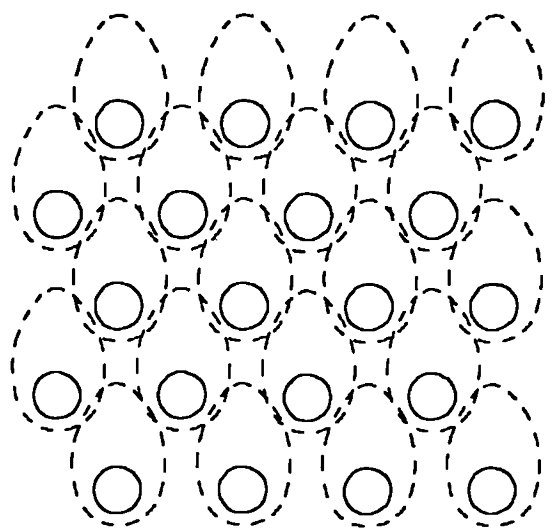

Figure 1.4 Klass and Martinek's double layer mechanism

Klass and Martinek further studied the electrical properties of electroviscous fluids [23] Results showed that electroviscous fluids under shear exhibited the characteristics of a small cell, that is, a steady-state voltage and current were produced. Although it was not suggested that conductivity was essential for the ER effect, their double layer mechanism required that mobile charge carriers must be available in the electroviscous fluids. Results also showed the increase in viscosity was accompanied by an increase in current and that the dielectric constant of the electroviscous fluid increased with increasing silica volume fraction.

Their electroviscous fluids [24], patented in 1967, consisted of:

1. At least 10 volume per cent of particulate silica having an average particle size in the range from 0.04 to 10 microns, the surfaces of the particulate silica having less than five silica-bonded hydroxyl groups per square millimicron of surface area.

2. Free water in the amount of 0 to 4 molecules per square millimicron of silica surface area.

3. A non-polar oleaginous vehicle which has a dielectric constant less than five and which is weakly absorbed by silica.

It was declared that, compared to Winslow's fluids, these fluids could be stored for a longer period of time without excessive deterioration, phase separation or reduction in electroactivity. These fluids could also stand a higher temperature for a longer time.

In 1968, Martinek [25,26] patented more compositions of ER fluids which are basically similar to that described in [24], except that a surfactant such as glycerol monooleate was added. Klass, in the meantime, also patented some new fluids [27] consisting essentially of about 30% by weight of white oil, about 50% by weight of silica having a particle size less than about 10 microns, about 5% by weight of ethylene glycol, and about 13.5% by weight of 1-hydroxyethyl-2-heptadecenyl-imidazoline, to which is added 1 to 40% by weight (based on the weight of the aforesaid components) of a particulate conductive metal having a particle size of less than about 30 microns.

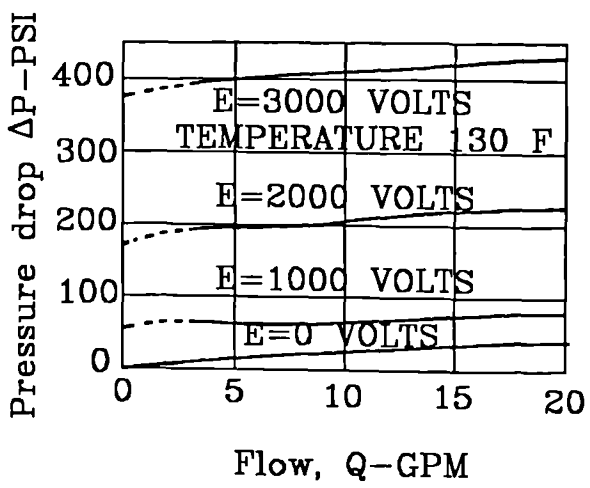

Figure 1.5 Strandrud's ER valve characteristic

In 1963, the first patent for a vibration shock absorber employing 'electroviscous' fluids was filed by Klass [28] Unfortunately, no practical applications occurred at that stage.

Strandrud [29] investigated an ER valve which consisted of narrow passageways formed by a nest of cylindrical shells with alternate shells were raised to a high potential. An interesting and important phenomenon was found with its flow characteristics and this is shown in Figure 1.5. As pressure drop is proportional to shear stress, these characteristics can be explained as follows: if the voltage applied to the valve is zero, shear stress is determined by Newton's law of viscous fluid flow, resulting in a proportional relationship between shear stress and shear rate. When the voltage is applied, shear stress is not proportional to shear rate, but is approximately a constant amount above the zero-voltage characteristic. This phenomenon was later referred to as the "Bingham effect".

1.3 Rapid Development in the 1970's

Since the 1970's, a large number of investigations into the ER fluids have been launched in many countries. Interest was re-awakened in the U.K. around 1967 [30] when a group lead by Royle and Bullough started to make their own fluids and related devices. This research was funded by the U.K. Ministry of Defence and thus results were not generally made available. In 1973, Bullough introduced this subject publicly [31] and since then more of their research results have been published [32,33] among which is a variably controllable, non-linear electroviscous damper in a vibration isolation system. At the same time, Stangroom at Sheffield University was concentrating on the development of ER fluids. Patents [34,35,36] show Stangroom's fluids comprise 30% to 35% by volume of alginic acid polymer in solid particulate form in which 6% to 12% by weight of water is absorbed. Although an electrically non-conducting oleaginous base oil was used, it is clear that these final fluids are water-bonded and thus are electrically semi-conducting.

By using the control of ER fluids, Gerrish filed patents [37,38,39,40] covering an ER damper, pile driving apparatus and seals.

In 1974, Okagawa, Cox and Mason [41] proposed a general theory for the rotation of a single ellipsoidal particle without Brownian motion in a flowing dielectric Newtonian fluid subjected to an electric field. It was shown that the particle experiences both hydrodynamic torque and electric torque, the latter resulting from permanent and induced polarisation of the particle. They pointed out that the polarisation and the orientation of the particles contributed to the viscosity enhancement under the application of the electric field.

Research in this field was reported in Japan as early as 1937 when Kimura [42,43] investigated the effect of an electric field on the viscosity of solutions rather than of pure liquids. A series of fluids, such as, benzene and hexane solution of lauric, myristic, stearic acid and of cetyl alcohol, was tested under the application of an electric field. It was found that the viscosity of these solutions increased with increasing field strength. Acid with longer chains showed a much more significant effect than those with shorter chains. With lauric acid, the viscosity increase showed a linear relation with applied field, whilst with stearic acid, the increase ceased at a certain voltage. Kimura attributed the effect to the contribution of the orientation of the molecules of the solute.

By testing the electro-fluids consisting of crystalline cellulose with an average radius of 5 microns and an insulating base oil of chlorine, Uejima [44] concluded that the dielectric constant increases linearly with the weight fraction of the particles. It was found that for the electroviscous effect to occur, it was necessary for a certain amount of water to be adsorbed both in the inner part and on the surface of the particle. Experimental results indicated that there existed an optimum amount of adsorbed water and particle weight concentration for the best results of relative viscosity, which was the ratio of apparent viscosity with electric field and that without electric field. Apparent viscosity was found to decrease with increasing frequency of applied field and yield shear stress was proportional to the square of field strength.

Uejima disagreed with Winslow's induced fibration explanation of the effect, indicating that the formation of fibre was unable to describe the quick response of an electro-fluid after application of an electric field. Similar to Klass and Martinek's "double layer" theory, Uejima indicated that when the dispersed particles in the electro-fluid were under the influence of an electric field, an interfacial electric double layer was formed around the particles which are strained and polarised. Due to an electrostatic attaction force occurring between these polarised electric double layers, the apparent viscosity of the fluid increases when there is relative motion of particles.

Honda and Sasada described the mechanism of electroviscosity from two aspects: the electrohydrodynamic effect on polar liquids [45], and the conductivity effect of dielectric liquids on electroviscosity [46] The influence of frequency on the ER effect [47] was also studied. It was shown that momentum in the electroviscous fluid, under the application of a perpendicular electric field, is not only transferred by molecular processes, i.e. viscosity, but also by convection. The convection effect is equivalent to an increase of viscosity.

With regard to the electroviscous effect under AC voltage, Honda and Sasada pointed out that there existed an injection cut-off frequency which was proportional to conductivity and applied field. For frequencies larger than the cut-off frequency, there was no injection, otherwise there was. Figure 1.6a shows the frequency effect on the relative increase in apparent viscosity of nitromethane. It can be seen that when frequency increases from zero to

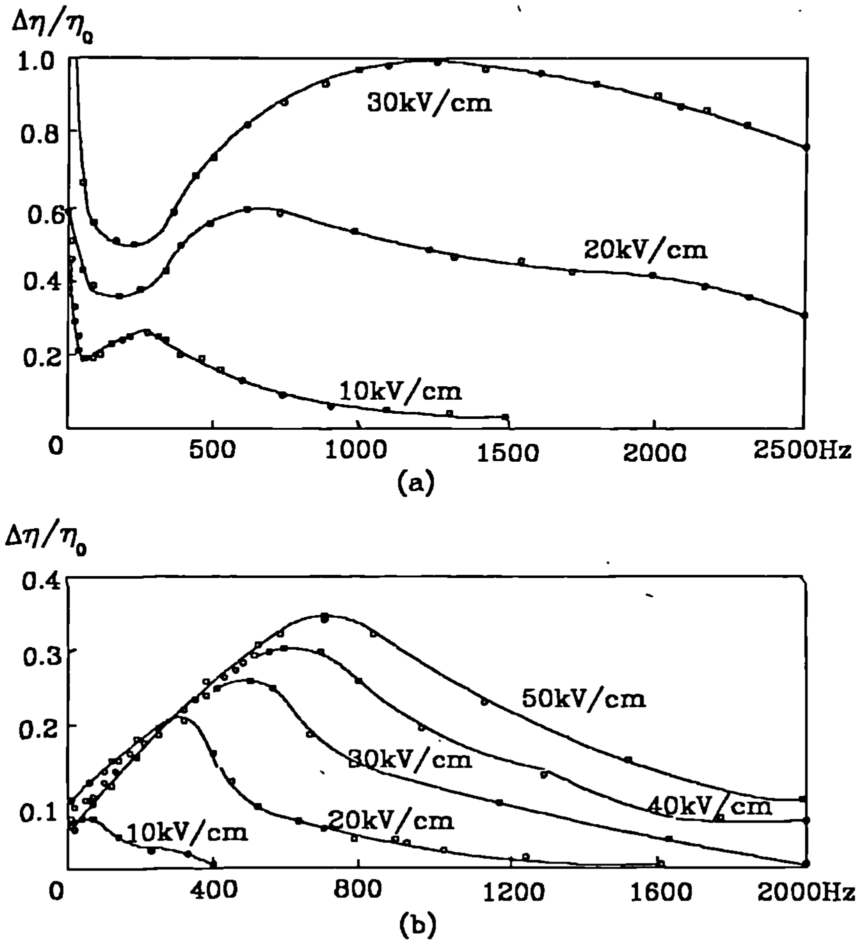

Figure 1.6 The effect of frequency on the increase of apparent viscosity. (a)--Nitromechane, (b)--Monochlorobenzene

2,500 Hz, the relative increase reduces from the maximum value: this is due to the existence of charge injection. The relative increase then increases to a peak and reduces again. The effect in this region could be attributed to the bulk-conduction due to the dissociated ions. The peak is due to the build up of space-charge layer in the vicinity of electrodes. under the application of high voltage. However, for fluids like 1,2-dichloroethane and monochlorobenzene, the relative increase increases to a peak and then decreases with frequency, as shown in Figure 1.6b. It was also found that the relative increase in apparent viscosity in some liquids like chloroform showed a constant decrease with frequency. It was concluded that in the case of injection, the increase of electric conductivity induced a monotonous increase in apparent viscosity. Whilst in bulk-conduction, there existed an optimum conductivity for the best apparent viscosity to be developed.

Fukuzawa et.al. studied the flows of EV fluids between two disks [48] and two cylinders [49] to determine the braking properties of EV clutches. Results showed that these devices were not of practical use due to the lack of strength of the ER fluids.

Based on the "double layer" mechanism, Sugimoto [50] developed new EV fluids in which an ionic exchange resin was used as the dispersion phase. It was demonstrated that these fluids not only produced the highest shear stress, but also exhibited better long term stability than previous fluids. The ionic exchange resin is a plastic polymer particle which has ionic exchange bases at the surface. The bases consist of fixed ions and counter ions which can freely exchange with other ions by ionic exchange reactions. Unlike previous dispersed phases, the ionic exchange resin produces a large shear stress with very low water content. This is probably one of the reasons that this kind of EV fluid is more stable. Studies showed that the larger particles provided a more stable EV effect than smaller particles; induced shear stress decreased with increasing field frequency. It seems that Sugimoto was the first to publish results of microscopical inspection on the EV fluid and show the particle chains linking electrodes under the application of voltage.

The interest of EV fluids was re-awakened in the Soviet Union in the 1970's. Shor et al [51] in 1975, studied the effect of an external electric field on the viscosity of lubricating oils and those containing polymer additives, by using a viscometer with an annular-section capillary formed by two coaxial electrodes. They achieved a two-fold increase in viscosity with certain oils when electrically stressed. These oils also showed a tendency towards an increase in viscosity when a dispersed phase with a high zeta potential was added. Maximum viscosity enhancement was observed at certain shear rates, which the authors suggested were due to electrification of the oil film and orientation of the oil molecules normal to the shear direction.

Deinega et al [52] studied experimentally the role of bound water in the ER effect by using a 25% suspension of potato starch in Vaseline oil. It was shown that there exists a maximum moisture content of the dispersed phase for the best ER effect to occur. As the electric field intensity increases, the positions of such maxima shift toward the lower moisture level.

Shul'man et al both qualitatively and quantitatively evaluated the structure formation in ER suspensions under the application of electric fields [53,54] It was pointed out that two types of inter-related charge carriers, which were present in the volume of particles or introduced with other compounds, could be attributed to the particles of ER suspensions. One of the charge carriers experiences little resistance in zones of contact, i.e. ensures conductivity through the particle bridges; the second type is, however, associated with high contact resistance. Their calculated results correspond well with experimental results. Silica gel and aerosol were used as particles. Water, alcohol, acid and diethylamine were used as activators. Cetane was used as the base oil.

Gorodkin et al [55] reported a series of applications of the ER effect in engineering practice and quoted nine Soviet patent applications granted in 1977 and 1978. These included a two-pump, two-valve vibrator, an electrohydraulic brake actuator, a safety valve, a generator of pressure fluctuations in a fluid, a colloid mill, and a peristaltic pump. Again, no practical application was realised.

Arguelles, Martin and Pick investigated both theoretically and experimentally electroviscous flow [56,57] Their results show that the electroviscous effect is proportional to the square of the applied field. It was pointed out that the most sensitive ER fluids have relatively high concentrations of particles (40-50% by volume) and with a particle size as small as possible.

In 1976, Westhaver patented a series of electroviscous fluids [58]. These fluids were formed by contaminating a dielectric base oil of low viscosity (5 to 15 centipoise at 100°F) with particles composed essentially of starch (corn, rice etc.) in the volume concentration of from 40 to 60%. 1 to 5% by weight of electrolyte and 1 to 5% by weight of water are absorbed in the particles.

1.4 Recent Explanations of the ER Mechanism

In the 1980's, both the developments in ER fluids themselves and their related applications marked a new era. This was mainly because the research attracted the chemical and automotive industries. The former was devoted to the production of ER fluids and the latter to applications, notably in torque transmission and vibration control.

An explanation for the mechanism of the ER effect is continuously pursued by many scientists as no satisfactory explanation has to-date been forthcoming. Atten and Honda [59] proposed an electrohydrodynamic explanation for the electroviscous effect in isotropic liquids which are free from macroscopic particles. It was suggested that electrically induced secondary motion was responsible for the increase in apparent viscosity, when subjecting a Poiseuille or Couette flow to an electric field. This secondary motion has a similar effect to turbulence in transfering momentum radially in a pipe and hence increasing the pressure drop. These experiments were limited to the case of strong unipolar injection in an insulating liquid and the results showed a strong magnification in pressure difference (apparent viscosity) by a factor of up to 20.

Arp, Foister and Mason [60] theoretically and experimentally studied some fluid dispersions under the application of electric fields. They concluded that electrohydrodynamic factors govern the motions and deformations of the suspended phase of these fluids.

In 1983, Stangroom [61] pointed out that the term 'electroviscosity' is inappropriate for the effect of an electric field on the flow of some fluids. He argued that when a voltage is applied to the electrode plates, just as the increase in the mechanical force pressing the two plates together leads to an increase in the dry friction force, so an increase in the voltage applied between the electrodes increases the force required to start and maintain movement. The term 'electrorheological fluid' is now popularly used.

Stangroom further argued that water was an essential ingredient in ER fluids. He stipulated that the minimum requirements for an ER fluid are that the base liquid must be hydrophobic, the solid must be hydrophilic and porous (so that it can contain an appreciable amount of absorbed water without being overtly wet) and that water must be absorbed on the solid particles. The amount of water absorbed greatly influences the properties of the final fluid.

It was noted by Stangroom that the magnitude of the current passing through the fluid could pose a serious problem. At a fixed voltage, the current doubles for each 6°C rise in temperature. One of the reasons was that the current increased with water content. The response time of an ER fluid to a step change in voltage was reported to be typically within 1 ms.

Stangroom proposed the electro-osmotic theory to explain the ER effect [62] This theory attributes all the rheological changes to a change in the interaction between particles and more specifically to the appearance of a short-range force of attraction between the particles. The force is in turn attributed to the water being displaced from within the particles by the electric field. However, this theory is not generally accepted. It was suggested that present ER fluids are best used at relatively low power density, at approximately uniform temperature and in those applications in which the essence of the problem is electronic control [63].

Block et al [64] studied the properties of some polymer dielectrics. It was found that permittivity changes with flow conditions. Also stimulated resonance of permittivity between electric field and shear rate field by a colloid system was observed. This phenomenon was used to explain the mechanism of the ER effect. When investigating the polarisation of rotating dielectrics which have a degree of asymmetry such as ellipsoids, rods, dumb-bells or string of spheres [65], Block and his colleagues pointed out that it was a serious limitation in some previous research to assume that time dependence of the polarisation of the particles did not show dielectric relaxation. This is because the dispersions showed maximum dielectric absorption at frequencies of the same order as the particle angular velocities induced by flows having practical shear rates. They further indicated that a rotating insulating dielectric sphere subjected to a constant electric field would show no mechanical torque if the relative permittivity has negligible frequency dependence. If however the material of the sphere has a finite electrical conductivity or should it exhibit dielectric absorption, the rotating sphere would experience a mechanical torque opposing the motion. A Couette cell was designed for the measurement of flow modified permittivity and electroviscosity [66]

More significantly, Block et. al. have developed some "dry" fluids which discard the 'essential' role of water in ER fluids [67]. It was pointed out that from the applications point of view, the existence of water would cause corrosion of devices, impose a limitation on operating temperatures and require a high power consumption. A patent on a dry ER fluid was filed in 1986 [68] This ER fluid comprises semiconducting particles which form an unsaturated fused polycyclic system. The base oil is a halogenated aromatic liquid containing water which occupies less than 5% by volume. The fluid is capable of developing a static yield stress of at least 0.5 kPa when the fluid is substantially anhydrous.

Gorodkin et al [69] found that variable geometries of electrodes offers a useful means of regulating the ER effect and that the loss of performance with fluid storage time is associated with structural changes in the fluid, such as coagulation.

Shul'man et al continued their investigation into the natures of charge carriers in ER suspensions [70]. They concluded that proton migration was the basic mechanism in the polarisation of the particles and thus in the ER effect.

Both D.C. fields and A.C. fields can be used to activate ER fluids. It has been demonstrated that an ER fluid can also be activated by a pulsed D.C. signal, Stevens et al [71,72] showed that the use of a pulsed D.C. supply can reduce the power consumption in ER devices.

A technique was developed to simultaneously measure the rheological and optical response of electrically stressed ER fluids in shear (Jordan, Wong and Shaw [73]). The rheo-optical results for a commercial ER fluid exhibited microstructural changes (occurring on application of the field) that are well within the time frame of the rheological response. However, it was pointed out that additional evidence was required to verify or refute particle fibrilation as the fundamental mechanism in the ER effect.

Ferrite suspensions in hydrocarbons show macrostructural polarisation under electric field (Fomenko et al [74]). It was demonstrated that effective ER systems can be developed by regulating the ferrite composition and adjusting the permittivity and conductivity.

Bullough, Firoozian and Peel [75] extensively studied the characteristics of ER fluids. They modelled an ER fluid by a resistor and a capacitor in parallel. Results showed that the model would be helpful for predicting the closed-loop stability, accuracy and performance of a system which uses an ER fluid as the medium in a valve controller.

By testing an ER fluid flowing through a parallel plate valve (0.5mm gap) subjected to a biased sine wave voltage excitation, Bullough and his colleagues studied the response of the ER fluid in the flow mode. It was found that the ER fluid resistance at high and low frequencies and also the time constant decreases with increasing frequency. [76]

Lingard and Bullough [77] suggested that ER fluids, for successful application in power hydraulic systems, need to be assessed for tribological properties as well as on bulk viscosity when boundary or mixed lubrication features are needed. It was pointed out that selection of a pure neutral base liquid is likely to cause unacceptable wear problems; particulates, although nominally of average size very much greater than contact film thickness, are able to traverse the contact. The base liquid and particles in ER fluids both contribute significantly to wear and friction behaviour.

1.5 ER Fluids in Engineering Applications

Apart from the investigation of ER fluids themselves, particular engineering applications of ER fluids were also widely carried out.

Power transmission seems to be the most obvious application to employ an ER fluid. Research in this field has been particularly active in Liverpool University since 1983, where a group lead by Sproston and Stanway progressively studied the properties and feasibility of some ER couplings (clutches) for torque transmission and braking [78,79,80,81] These results show that transmitted torque generally increases with applied electric field but can be limited by electrical discharge occurring in the devices. The influence of temperature on transmitted torque shows that a peak torque occurs within the range of 50-55°C for typical ER fluids when the applied voltage is constant. These investigation demonstrate conclusively that ER clutches (couplings) can achieve a controlled variable output speed. Transmitted torques of up to 4 Nm and an output speed of 0 to 1500 rpm have been achieved with devices having a single pair of disks.

Shulman et al studied the damping of mechanical-systems oscillations with an ER fluid [82] Their theoretical and experimental analyses show the efficiency of using an ER fluid applied with an electric field for ensuring high damping and temporary characteristics in the field of low frequencies and small-amplitude strains. The possibility of designing an active suspension system was considered.

Anaskin et al [83] investigated the amplitude-frequency characteristic of a viscous damper using an ER fluid controlled by an external electric field.

They found that the effectiveness in reducing the amplitudes of vibrations and in appreciably shortening the damping time was much higher using an ER damper than by conventional means. It was shown possible to suppress vibrations with various initial amplitudes to a given desired level.

Dampers and adaptive suspension systems using ER fluids as damping media are most likely to realise variable damping characteristics. Experimental and theoretical results by Stanway and Sproston et al [84,85,86,87] revealed that a wide range of damping can be obtained from a single ER damper by controlling the applied potential. It is suggested that the combination of a viscous and Coulomb model is valid over the normal working range of an ER damper (between 1kV/mm and 2 kV/mm) [85] At lower field strengths a viscous damping model was shown to be satisfactory whilst at higher field strength the damper was seen to be direction-dependent. It was found that parameters in an n^{th}-power velocity damping model can be estimated using a non-linear filtering technique [87]

Stevens' Ph.D. thesis [88] generally summarised those researches carried out in Liverpool University.

Choi, Thompson and Gandhi [89,90,91] investigated both theoretically and experimentally a new class of 'smart' structural materials containing voids filled with ER fluids for vibration control applications. It was shown that the elastodynamic behaviour could be actively controllable by selectively tuning the applied field to the ER fluid in the structure.

Stangroom [92] applied ER fluids in improved pipework snubbers in which the electrical detection of seismic events was combined with relatively simple mechanical construction. these devices offer the possibility of optimising the response to disturbances, as well as improved reliability and reduced initial and maintenance costs.

To apply ER fluids in robotics is a new topic introduced in the 1980's. Kenaley and Cutkosky [93] fabricated and tested robotic "fingertips" which consisted of a layer of ER fluid sandwiched between a grounded elastomer skin and a positively charged electrode. The ER fingertips could be employed on a robot gripper or the fingers of a dextrous robot hand. As the ER fluid solidifies with increasing voltage applied to it, the finger has simple tactile sensing and is able to generate large lifting forces with small grasp forces, due to interlocking between the deformed skin/solidified fluid and the gripped object. A gripper with ER fingertips was able to grip a raw egg gently using capacitance sensing.

Gandhi et al [94] studied the electrodynamic response of flexible multibodied articulating systems fabricated with some advanced materials in which an ER fluid was incorporated. This idea was experimentally validated and computer simulations demonstrated the significant advantages of fabricating robot arms using the advanced materials.

Brooks further developed the idea of ER hydraulic control valves [95,96,97] Having noted that a single valve has limited use, a hydraulic circuit using four ER valves to form a Wheatstone bridge arrangement was then designed. This is shown schematically in Figure 1.7. This valve bridge could be used to control the motion of a hydraulic cylinder. A series of dampers and clutches were tested and showed good performance. Endurance testing of the ER fluid in excess of 5000 hours showed no significant deterioration of performance,

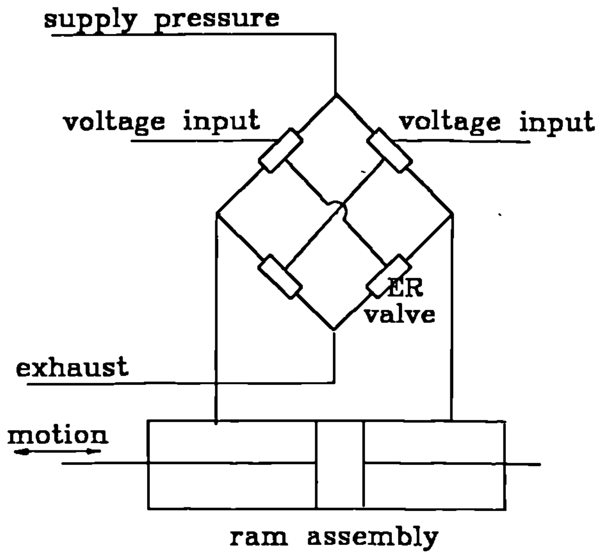

Figure 1.7 Brook's Wheatstone bridge of ER valves

neither had the performance of a four-valve actuator deteriorated over a two-year period. It was suggested that ER fluids could soon revolutionise hydraulic equipment [98]

ER fluids make it possible to fabricate some ultra-advanced intelligent composite materials (Gandhi et al [99,100]). Evaluation is made on the static and elastodynamic transient response characteristics of a cantilevered beam fabricated from ER fluids. Results demonstrated the ability to dramatically change the vibrational characteristics of the beam-like specimens. These materials were proved to be capable of interfacing with modern solid-state electronics.

It is worth mentioning that since 1985, a regular international conference on electrorheological fluids and related engineering application has been held [100,101]. The conference will help the development of ER technology.

1.6 Prospects of ER Fluids and their Engineering Applications

Fifty years after Winslow's pioneering attempts to employ ER fluids in practical engineering applications, both the fluids and related applications have advanced a great deal towards the point of commercial exploitation. Many different ER fluids have been tested and different excitation waveforms have been used. These, together with typical devices which were built to evaluate the applicability of ER fluids, are summarised in the following Tables.

Previous researches in ER fluids and related engineering applications have lead to conclusions concerning some important requirements of the ER fluids [102,103]:

1. The ER fluid should provide a high shear stress at low maximum electric field and a very low shear stress with no electric field. These requirements are possibly the most essential in engineering applications like power transmission and hydraulic control valves.

2. The fluid properties should ideally remain stable over as wide a temperature range as possible, typically from $-20°C$ to $+140°C$.

3. The fluid should not settle down either in storage or in an application with centrifugal force (or be readily agitated when the mechanical excitation is applied).

4. The base oils should be non-toxic, non-flammable, of low volatility and should also be non-corrosive to device construction materials and seals.

5. Except in so far as fulfilling the above mentioned requirements, the particles in the ER fluid should be soft enough so as not to cause excessive wear and abrasion.

Although the current commercially available ER fluids can not entirely meet the above requirements, many companies like Lord Corporation, ICI, American Cyanamid, Ford, GM and Mercedes have been active in the development of ER fluids and their applications [104]. It has been reported that the first commercial application based on ER fluids will be in 1991-1993. The impact might perhaps capture up to 50% of the hydraulic market [105] It is also reported that in the year 2000, the fluid itself is expected to have a $12,000 million world market [106].

Dispersed Phase	Base liquid	Additive	Refer-ence
Alginic acid	Polychlorinated biphenyls, poly(tri-fluorovinyl chloride), o-dichlorobenzene, p-chlorotoluene, xylene, and mixture of above	Water	34
Calcium titanate	Naphthenic oil	Non-ionic surfactant	22
Carbon	Transformer oil, olive oil or mineral oil		18
Carboxymethyl dextran	Polychlorinated biphenyls or poly(trifluorovinyl chloride), o-dichlorobenzene or xylene or mixtures of the above	Water and sorbitan mono-oleate or sorbitan mono-sesquioleate	107
Cellulose	Chlorinated insulator oil liquid paraffin or hydraulic oil dibutyl sebacate or oleic acid or chlorotoluene or silcone oil	Water	44
montmorillonite, vermiculite,	Vaseline oil	Water	44
polygorskite	Lubricating oil	Water	55
Copper phthalo-cyanine	Paraffin grease or silicon oil	None	68,107, 108
Gelatine	Transformer oil or olive oil or mineral oil		18
Gypsum	Transformer oil or olive oil or mineral oil		18

Ion exchange resins--strong and weak, acid and base unspecified	Di-n-butylphthalate or di-n-octylphthalate or di-n-decylphthalate or di-isodecylphthalate or tri-n-octyl trimellitate or tri-2-ethylhexyl trimellitate or tri-isodecyl trimellitate or tri-cresyl phosphate	Water	50
Iron(II) oxide	Petroleum fractions or dibutyl sebacate or di-2-ethylhexyl adipate	Water and surfactant	19
Iron(III) oxide	Petroleum fractions or dibutyl sebacate or di-2-ethylhexyl adipate	Water and surfactant	19
Lime	Transformer oil or olive oil or mineral oil		18
Phthalocyanine	Silicone oil	None	108
Poly(acene-quinone radicals) based on anthracene or naphthalene or terphenyl or ferrocene or pyrene or phenanthrene	Chlorinated hydrocarbons or liquid paraffin/paraffin grease or silicone oils	None	68,108
Poly(acrylic acid) cross linked with divinyl benzene--as lithium salt	Chlorinated hydrocarbons or fluorolube FS-5		36
Poly(methacrylic acid) as lithium salt	Chlorinated hydrocarbons or fluorolube FS-5	Water	36

Poly(methacrylic acid) cross-linked with divinyl benzene lithium or guanidium or mixed lithium/chromium salt	Chlorinated hydrocarbons or fluorolube FS-5	Water	36
Silica	Kerosene or dibutyl sebacate	Water and soaps, sorbitol or fatty acid esters	17,19
Silica	Naphthenic oils	Non-ionic surfactant	22,23
Silica	Mineral oil or xylene or silicone oil	Water and glycerol oleates	21
Silica	Petroleum distillate or transformer oil or silicone oil	Water or water/glycerol and surfactant	25,26,27
Sodium carboxymethyl cellulose	Paraffin or silicone oils	Water	107,108
Sodium carboxymethyl dextran	Polychlorinated biphenyls or poly(tri-fluorovinylchloride) or o-dichlorobenzene or p-chlorotoluene or xylene or mixtures of the above	Water and sorbitan mono-oleate or sorbitan mono-sesquioleate	34
Starch(flour)	Mineral or transfor-mer oil or olive oil		18
Starch(flour)	Petroleum spirit or transformer oil	Water and sorbitan oleate or laureate	58
Starch(flour)	Hydrocarbons or Vaseline oil	Water	52
Starch (non-flour)--unspecified	Silicone oil		71,81,88

Stone	Transformer oil or olive oil or mineral oil		18
Sulphopropyl dextran	Polychlorinated biphenyls or poly(trifluorovinyl chloride) or o-dicholorobenzene or xylene or mixtures of the above	Water and sorbitan mono-oleate or sorbitan mono-sesquioleate	34
Tin(II) oxide	Petroleum fractions or dibutyl sebacate or di-2-ethylhexyl adipate	Water and a surfactant	19

Table 1.1 Different ER Fluids Used by Previous Researchers

Type of electric field	Reference	Comments
DC electric field	7,8,12,15,22,45,81, etc.	Most popularly used
Pulsed DC electric field	71	Reduction of power consumption
AC electric field	8,12,22,47,75, etc.	Popularly used. Generally not as effective as DC field

Table 1.2 Different Electric Fields

ER devices	Reference	Comments
Clutch, coupling, power transmission devices	17,20,48,49,79-81,88	Potential applications
Damper and shock absorber	17,24,33,38,39,55, 81-91	Optimism application
Hydraulic control valve	19,29,55,94-97	Pressure too low
Robotics devices	92,93	Potential application
Composite material	98,99	Potential application

Table 1.3 Different ER Devices

1.7 Objectives and Scope of the Thesis

ER fluids and their engineering applications have formed postgraduate research topics on several occasions [88,107,108]. However, these investigations only concentrated on the basic properties of the fluids and the tests of preliminary engineering application concepts using the fluids.

The present work focuses on two objectives: one is the theoretical analysis and concept development; the other is experimental investigation of these concepts towards practical applications.

Theoretical analysis on the properties of the ER fluids and factors influencing the ER effect is based upon an ER model consisting of a capacitor formed by the ER device, the resistance of the ER fluid and the resistance of the circuit of the ER system. Theoretical analyses are also presented for ER power transmission and an ER vibration damper.

Two new ER application concepts are developed, i.e., an ER universal control valve and an ER mechanical power transmission device.

Experiments are presented on ER power transmission devices involve three couplings: a single plate ER brake, a single plate ER cooling fan drive and a multiplate ER drive shaft. The experimental study on ER dampers is based on a multicylindrical ER damper. The above topics are arranged in the main body of the thesis as follows:

Chapter One is the Introduction, which has been presented above. In Chapter Two a theoretical analysis is presented to evaluate how different factors influence the ER effect. Theoretical and experimental aspects of power transmission using ER fluids are considered in Chapter Three. Chapter Four focuses on the concept development of ER mechanical power transmission which involves a combination of an ER coupling with a mechanical gear train. Chapter Five describes the theoretical and experimental analyses of ER dampers and adaptive suspension systems. In Chapter Six the concepts of an ER universal control valve and other control valves are developed.Finally, general conclusions and suggestions for further researches in ER technology are given in Chapter Seven.

CHAPTER 2

THEORETICAL ANALYSIS OF ER EFFECT

2.1 Introduction

As indicated in Section 1.1, ER fluids consist either of pure polymer dielectric liquids or the suspension of some particles in insulating polymer oils. The commonly used carriers are polymer oils which are not electrically conducting. However, there is a variety of particles, some are "dry" and thus practically non-conducting; others are adsorbed with water and thus show some conductivity. In the following analysis, the details of the ER fluid compositions will be neglected, rather attention will be focused on the ER fluid as part of an ER system.

How different factors influence the ER effect will be explained on the basis of the analyses of two ER model circuits. It will be shown why viscosity is chosen as the parameter which is generally used in engineering to describe an electrically excited ER fluid. Behaviour of ER fluids under the applications of DC and AC fields are discussed in detail, whilst the comparison of the two situations will show which field is the better. It is shown that an increase of temperature will lead to an increase in current passing through the fluid.

2.2 Factors Which Influence the ER Effect

2.2.1 The Establishment of ER Models

For an ER effect to occur, the following elements are neccssary: an ER fluid which may be assumed to be conducting or non-conducting; two electrodes between which the fluid is evenly distributed; a power supply which generates an electric potential applied to the electrodes and thus subjects the ER fluid to an electric field. These elements are schematically shown in Figure 2.1a and Figure 2.1b, where the former is an ER system with non-conducting ER fluid and the latter is an equivalent circuit of an ER system with conducting fluid of resistance r. It should be noted that a typical conducting fluid has a resistivity of $10^8\Omega cm$. R represents the resistance of the circuit, including the internal resistance of the power source and that of the connecting wires. C is the capacitance of the capacitor formed by the electrodes and the ER fluid. d is the gap between the electrodes and v is the voltage supplied by the power source which may be direct or alternating current (DC or AC).

2.2.2 Factors Which Influence the ER Effect

There are two types of factor which influence the ER effect, namely internal factors associated with the ER fluid itself and external factors associated with the electrical circuit. Internal factors include the original (electrically un-stressed) viscosity of the ER fluid itself, μ_0 , which is determined by the viscosity of the base oil and the particle mass ratio in the fluid; the conductivity of the ER fluid, σ, or the resistance of the ER fluid, r; and the permittivity of the ER fluid, ε. External factors include the electric field

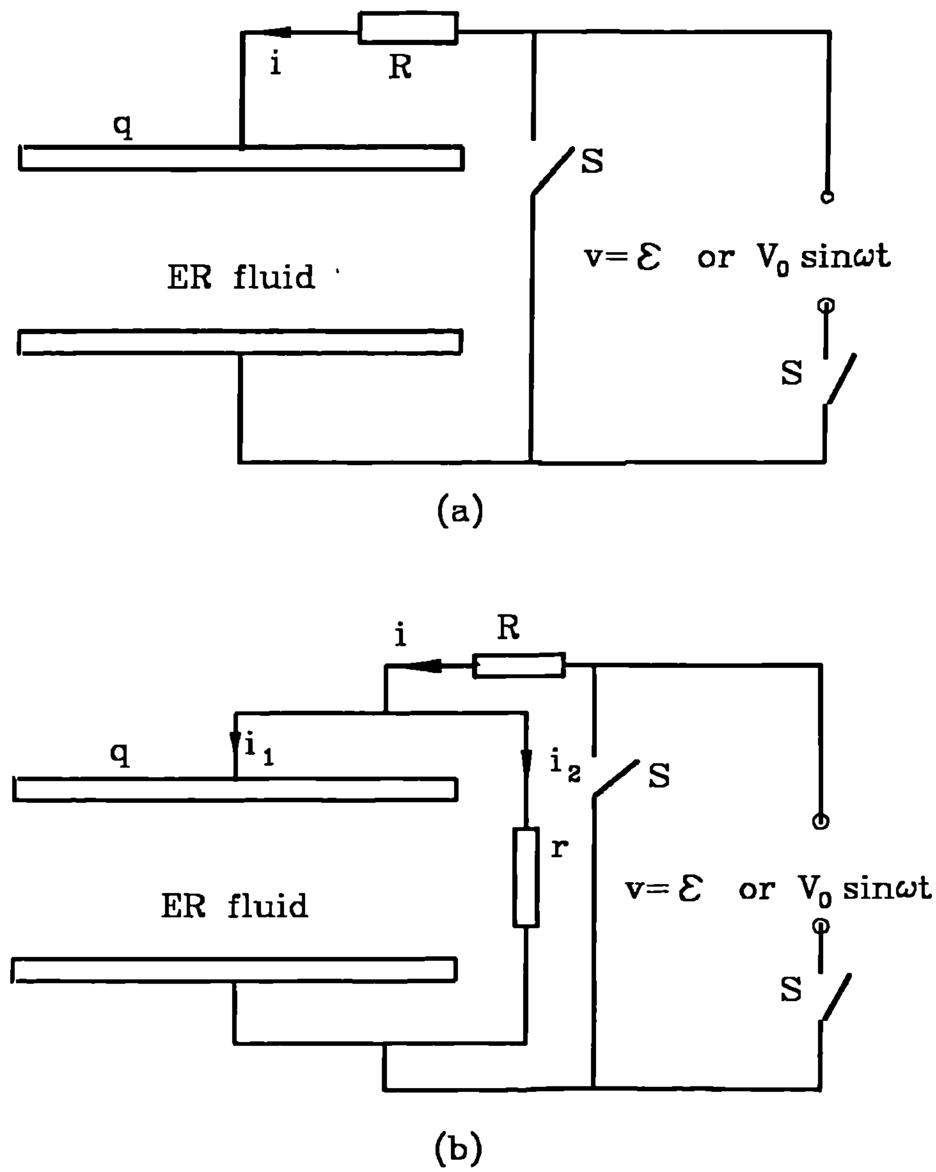

Figure 2.1: Two Models of ER circuits (a)with non-conducting fluid, (b)with conducting fluid.

strength, E, applied to the electrodes; the current, i, passing through the fluid or the power consumed, p; the angular frequency of the power source, ω, and the resistance of the circuit, R. How these factors influence the ER effect is a question which will be answered later. However, it should be noted that the higher the electric field which can be applied to the ER fluid, the better the ER effect achieved.

2.3 The Apparent Viscosity of an ER Fluid

For convenience of discussion, a DC field applied to the model shown in Figure 2.1a, i.e., with non-conducting ER fluid, will be chosen to analyse the apparent viscosity of an electrically-activated fluid. Stangroom [61] indicated that the increase in apparent *viscosity is not accurate enough to describe the* ER phenomenon. This theory might be correct from a chemical or a molecular point of view, but from an engineering point of view, it would be advantageous if one parameter could be used to describe the state of an ER fluid at different applied field strengths. It appears that the apparent viscosity increases when the fluid is under a high field, because the shear stress increases. Especially when the applied electric field is low or there is a small number of particles in the fluid, the friction of the fluid is more like viscous friction than Coulomb friction [81]. Thus under these circumstances it is appropriate to describe the ER effect in terms of its apparent viscosity.

When the electric field is applied, the particles in the ER fluid will be polarised. This polarisation means that an attractive force is imposed between the particles and the electrodes. It is known that the viscosity of a fluid is

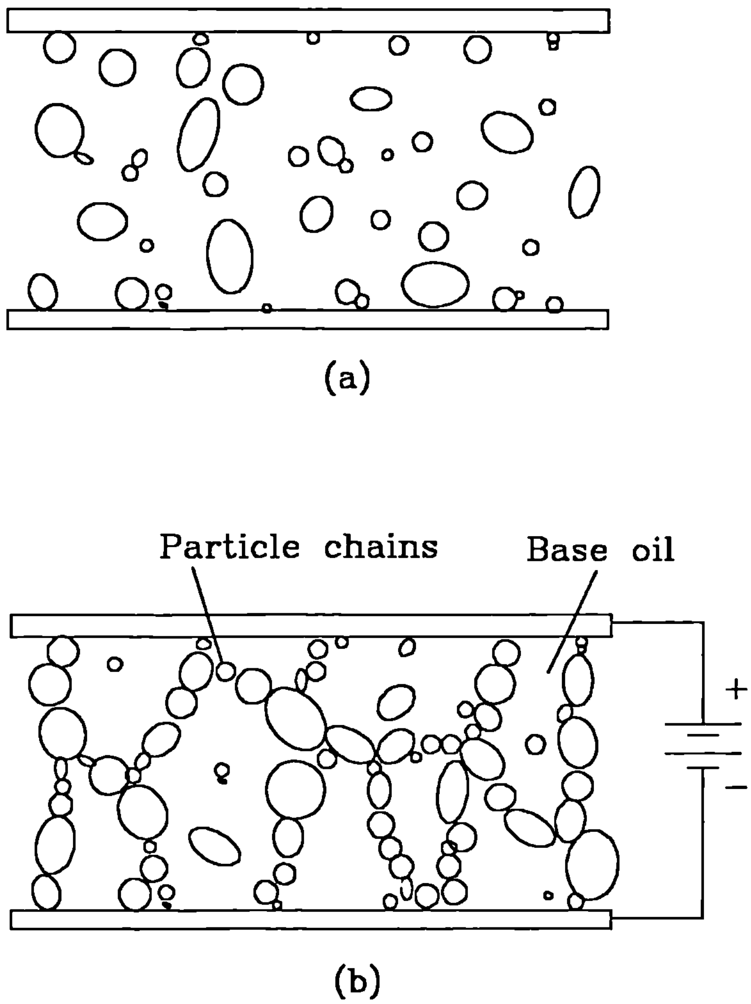

Figure 2.2: A microscopic view of the ER effect (a) without applied electric field, (b) with applied electric field.

mainly as a result of the molecular attractive forces. When the field is removed, there is no additional attractive force between the electrodes and particles and the particles are randomly suspended in the base oil. Thus the ER fluid returns to its original viscosity. However, when the ER fluid is polarised, an extra attractive force is exerted between the polarised particles which form a series of chains linking the electrodes and thus enhance the apparent viscosity. The existence of polarised particle chains has been observed by many previous researchers [50,88]. This is shown in Figure 2.2 which is reproduced from microscopic photographs. Therefore, it can be assumed that the larger the attractive force between particles and electrodes, the larger the apparent viscosity.

2.4 The Response Time of the ER Effect

Response time and apparent viscosity are the two most important parameters in the ER effect. It has been suggested that the ER response time is within a few milliseconds [2]. To define the response of an ER fluid, it is important to specify the parameter which can be used to characterise the state of the ER effect when the fluid is fully "solidified". It seems reasonable to suggest that when the electric charge on the particles is a maximum, the attractive force is also a maximum, and the fluid's response has reached a steady-state condition. Therefore, in this analysis, we assume that when an electric field is applied to an ER fluid, the time needed for the electric charge on the electrodes to rise to the maximum is used to characterise its performance.

2.4.1 Charging Response Time

Again the simplest model is used for the discussion, i.e. a non-conducting fluid subjected to a DC field. With reference to Figure 2.1a, we assume that at any time t, the instantaneous current is i and the instantaneous charge that has accumulated on the capacitor is q. We then have:

$$\mathcal{E} = iR + \frac{q}{C} \tag{2.1}$$

or

$$\mathcal{E} = R\frac{dq}{dt} + \frac{q}{C} \tag{2.2}$$

The solution to equation (2.2) is:

$$q = C\mathcal{E} - C\mathcal{E}e^{-t/CR}. \tag{2.3}$$

When t = 0, the charge accumulated on the electrodes is zero. As t increases, so q will increase until it reaches its maximum value $C\mathcal{E}$ when the polarisation process is finished. The time needed for this process is called the charging time. Figure 2.3 shows the process.[1] Since it is an asymptotic process, we define the response time as $0.9C\mathcal{E}$, i.e. the time needed for the charge to increase to 90% of its maximum value:

$$t_r = -RCln0.1 = RC\ln 10 = R\frac{A\varepsilon}{d}\ln 10 \tag{2.4}$$

---

[1] Figures 2.3 to 2.10 are plotted on the theoretical calculations using the related equations with $R = 100\Omega$, $r = 10^6\Omega$, $f = 10Hz$, $C = 10^{-5}F$, $V_0 = 6000V$, $\mathcal{E} = 6000/\sqrt{2}\,V$.

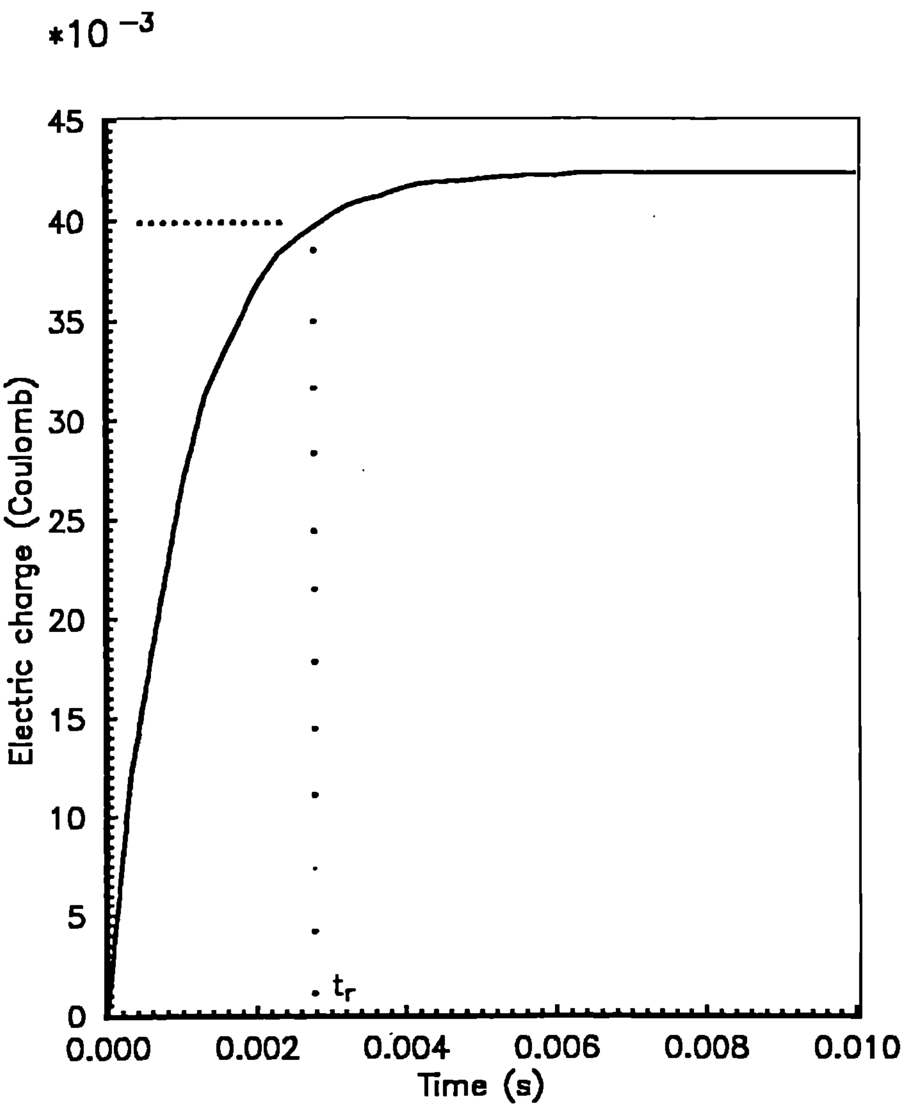

Figure 2.3: Characteristic of ER time response

2.4.2 Discharging Response Time

When a fully charged ER device has the power supply cut and dischaged, the time needed for the charge to decrease to one tenth of its maximum value is defined as the discharging response time. This turns out to be the same as the charging response time.

It is clear that when an ER device is designed, its response time is proportional to the permittivity of the ER fluid employed. For a short response time, it is better to use a fluid with low permittivity, but for a larger apparent viscosity, it is better to use a fluid with higher permittivity. A compromise will have to be made according to the eventual application.

2.5 ER Effect Under DC Field

2.5.1 With Non-conducting ER Fluid

Figure 2.1a shows the case when a non-conducting ER fluid is subjected to a DC field. As can be seen from equation (2.3), the steady-state charge on the electrodes is $C\mathcal{E}$ and there is no steady-state current in the circuit, as long as the potential of the DC power source does not change. Thus the steady-state field strength on the fluid is:

$$E_{dc}^{\infty} = \frac{\mathcal{E}}{d} \tag{2.5}$$

and the steady-state current passing through the ER fluid and the power consumed are zero.

2.5.2 With Conducting Fluid

This case is shown in Figure 2.1b. The equations for the circuit are then given by

$$\mathcal{E} = iR + \frac{q}{C} \tag{2.6a}$$

$$i_1 = \frac{dq}{dt} \tag{2.6b}$$

$$i_2 r = \frac{q}{C} \tag{2.6c}$$

$$i = i_1 + i_2. \tag{2.6d}$$

This yields:

$$\mathcal{E} = R\frac{dq}{dt} + \frac{q}{\frac{Cr}{R+r}} \tag{2.7}$$

The solution to equation (2.7) is

$$q = \frac{C\mathcal{E}r}{R+r} + \frac{C\mathcal{E}r}{R+r} e^{-t/(\frac{CRr}{R+r})}. \tag{2.8}$$

Then the steady-state field strength applied on an ER device is

$$E_{dc}{}^{\infty} = \frac{q^{\infty}}{Cd} = \frac{r\mathcal{E}}{(R+r)d} \tag{2.9}$$

the steady-state current passing through the ER fluid is

$$i_{dc}{}^{\infty} = \frac{E_{dc}{}^{\infty}d}{r} = \frac{\mathcal{E}}{(R+r)} \tag{2.10}$$

and the steady-state power consumed by the ER fluid is

$$p_{dc}^{\infty} = (i_{dc}^{\infty})^2 r = \frac{\varepsilon^2 r}{(R+r)^2} . \tag{2.11}$$

The analysis shows that the field strength for an applied DC potential, whether with a conducting or non-conducting ER fluid, is independent of the permittivity or the capacitance of the ER fluid. Also, current and power are independent of permittivity. If the ER fluid is non-conducting, the field strength is dependent on the voltage of the power source and the gap between the electrodes, as shown in equation (2.5). There is no steady-state current passing through the ER fluid as is understandable and thus there is no steady-state power consumption.

However, if the fluid is conducting, the field strength, current and power are not only dependent on the resistance of the fluid itself, but also on that of the circuit. The relationships are shown, respectively, in Figures 2.4 and 2.5. It can be seen from Figure 2.4 (a) and (b) that the increase of ER fluid resistance leads to an increase in field strength and a decrease in current. There exists an optimum fluid resistance $R = r$. Before this point is reached the power consumed by the ER fluid increases with increasing fluid resistance. Beyond this point power consumption decreases with increasing fluid resistance. In practice, this maximum power consumption point can be avoided because the usual resistance of the ER fluid is much larger than that of the circuit, i.e. $r >> R$. When the resistance of the fluid is large enough, current and power tends to zero and field strength tends to a maximum value of $\frac{\varepsilon}{d}$.

As shown in Figure 2.5, the increase in circuit resistance leads to a decrease in steady-state field strength, current and power. It is clear that in order to

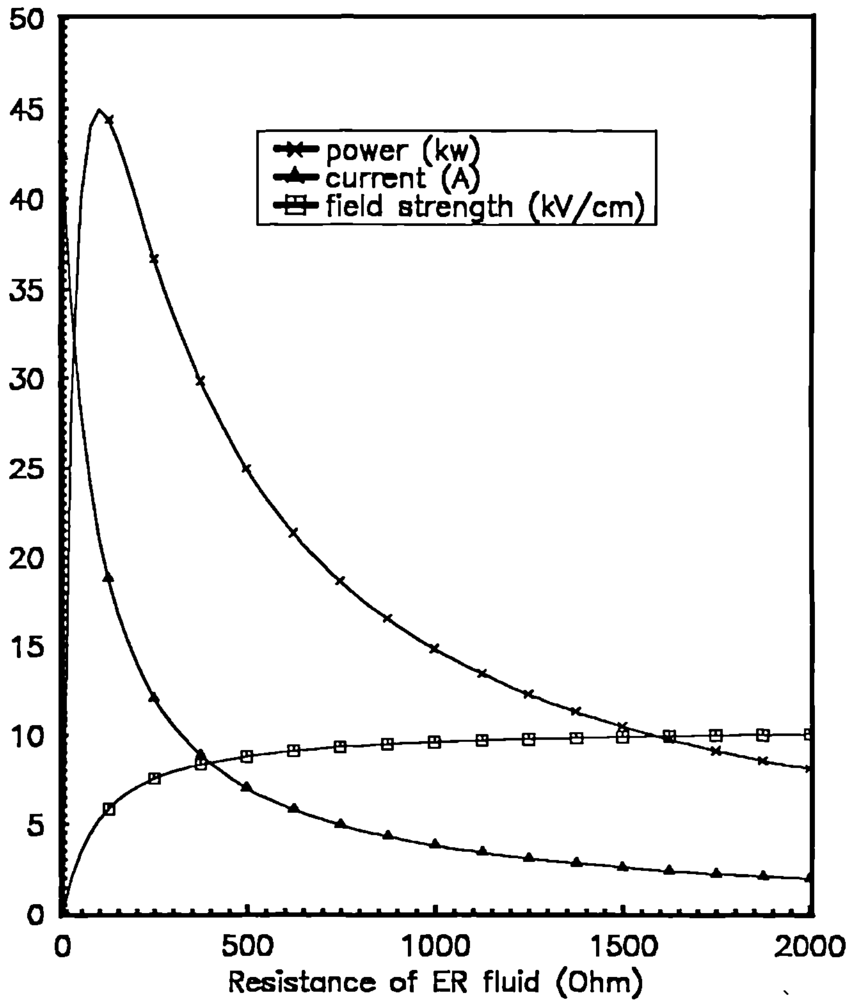

Figure 2.4a: The influence of ER fluid resistance on field strength, current and power

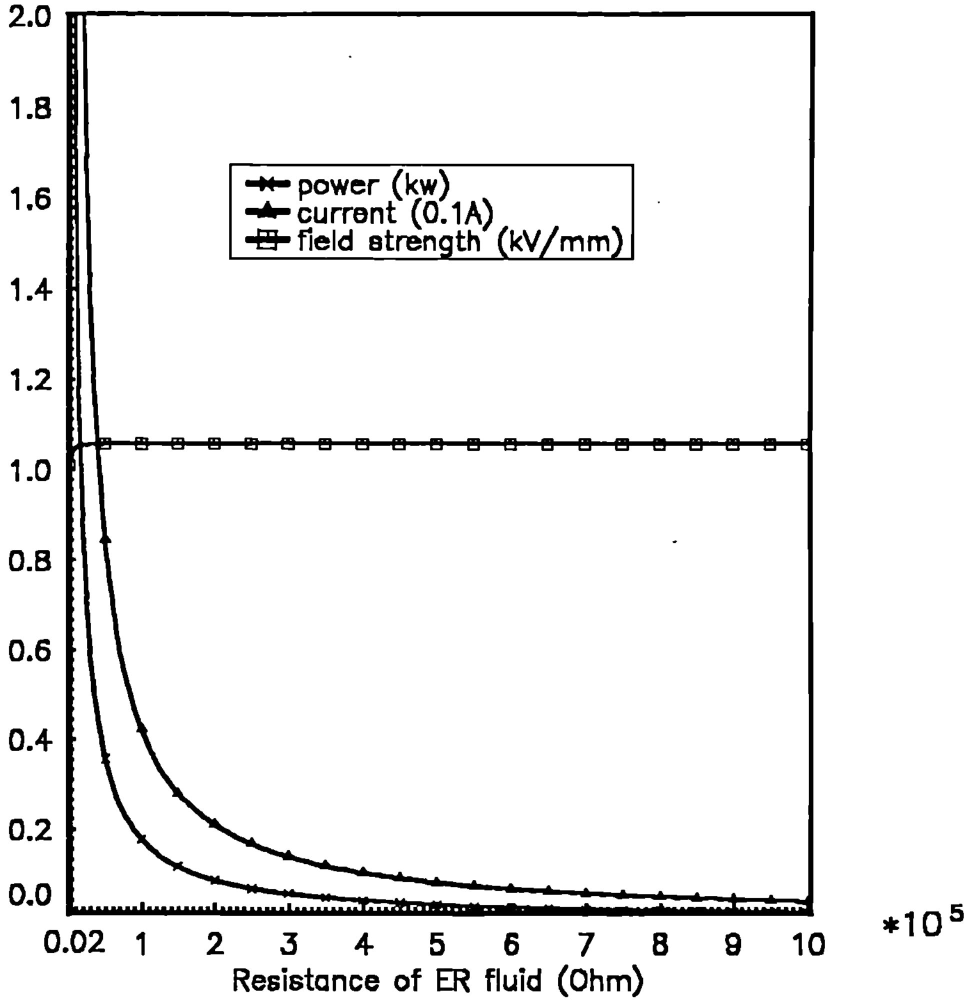

Figure 2.4b: The influence of ER fluid resistance on field strength, current and power

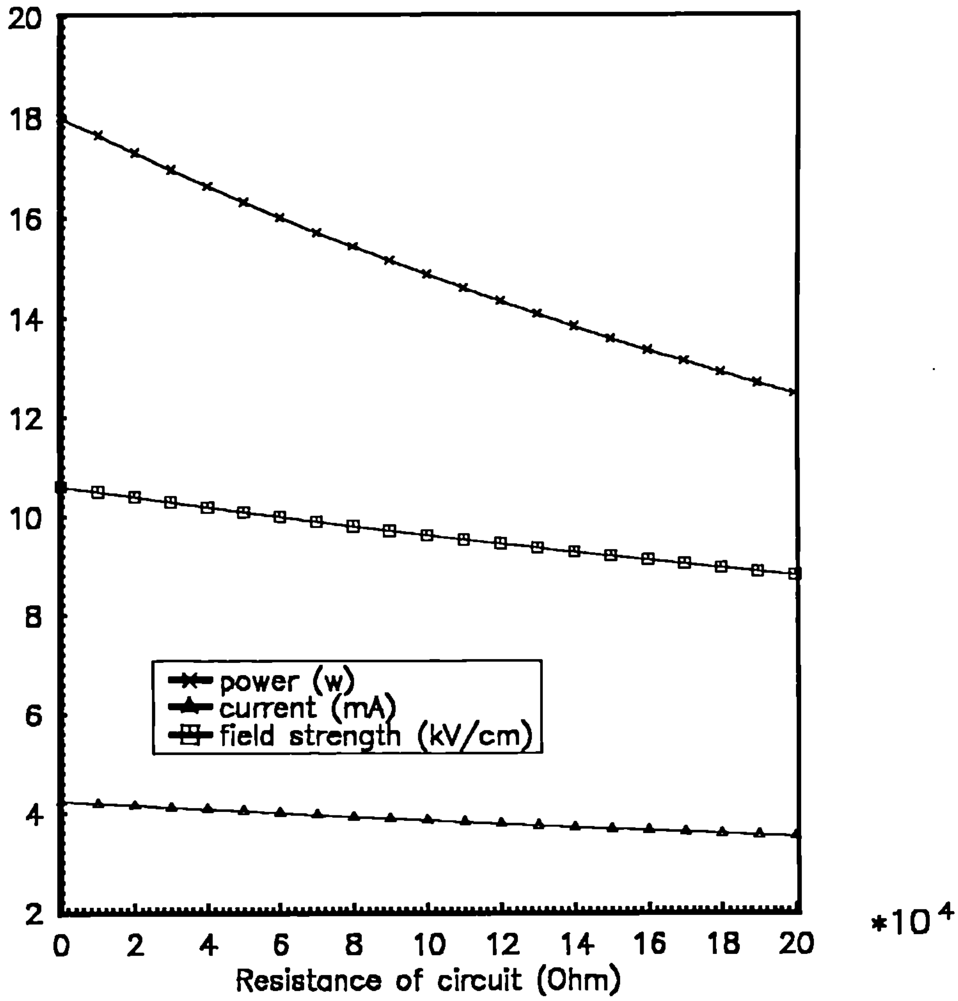

Figure 2.5: The influence of ER circuit resistance on field strength, current and power

achieve a high field strength, the circuit resistance should be made as small as possible.

2.6 ER Effect Under AC Field

2.6.1 With Non-conducting ER Fluids

Here it is assumed that not only is the resistance of the ER fluid very large, but also the resistance is much larger than the capacitive reactance $\frac{1}{C\omega}$. In Figure 2.1a, it is assumed that there is a sinusoidal potential difference applied to the ER circuit, that is:

$$v = V_0 \sin \omega t \tag{2.12}$$

Then the equation of the circuit is:

$$V_0 \sin \omega t = iR + \frac{q}{C} = R\frac{dq}{dt} + \frac{q}{C} \tag{2.13}$$

and the solution is:

$$q = Ke^{-t/RC} + \frac{CV_0 \sin(\omega t - \alpha)}{\sqrt{1 + R^2C^2\omega^2}} \tag{2.14}$$

where

$$\alpha = \tan^{-1} RC\omega. \tag{2.15}$$

As both the positive and negative half cycles of $\sin(\omega t - \alpha)$ has the same effect on ER devices, the mean value of its positive half cycle, i.e., $\frac{2}{\pi}\cos\alpha$, is used for the following calculations and equations. So is the mean value of $\cos(\omega t - \alpha)$. The first term on the right of equation (2.14) is zero at steady state, i.e., when $t \to \infty$, then the mean value of electric field at steady state is

$$\bar{E}_{ac}{}^{\infty} = \frac{\bar{q}^{\infty}}{Cd} = \frac{2V_0}{\pi d(1 + \omega^2 R^2 C^2)} \tag{2.16}$$

The steady-state current passing through the ER fluid is

$$i_{ac}{}^{\infty} = \left(\frac{dq}{dt}\right)_{t=\infty} = \frac{CV_0\omega\cos(\omega t - \alpha)}{\sqrt{1 + R^2C^2\omega^2}} \tag{2.17}$$

which yields a steady-state mean current

$$\bar{i}_{ac}{}^{\infty} = \frac{2R\omega^2C^2V_0}{\pi(1 + R^2C^2\omega^2)}. \tag{2.18}$$

The mean value of steady-state power consumed by the ER fluid is zero, that is, all the power is consumed by the resistance R.

2.6.2 With Conducting ER Fluid

This situation is shown in Figure 2.1b. The equation to the circuit can therefore be written as

$$V_0 \sin\omega t = R\frac{dq}{dt} + \frac{q}{\dfrac{Cr}{R+r}}. \tag{2.19}$$

Similar to the solution of equation (2.13), we then have

$$q^{\infty} = \frac{V_0 \sin(\omega t - \beta)}{\sqrt{(\frac{R+r}{Cr})^2 + R^2\omega^2}} \tag{2.20}$$

where

$$\beta = \tan^{-1} \frac{\omega RrC}{R+r}. \tag{2.21}$$

and the mean value of the steady-state field strength is then

$$\overline{E}_{ac}{}^{\infty} = \frac{2V_0}{\pi d(\frac{r+R}{r} + \frac{R^2\omega^2C^2r}{R+r})} \tag{2.22}$$

and the steady-state current passing through the fluid is

$$i_{ac}{}^{\infty} = \frac{V_0\sqrt{1 + r^2C^2\omega^2}}{\sqrt{(R+r)^2 + R^2r^2C^2\omega^2}} \sin(\omega t - \beta + \gamma) \tag{2.23}$$

where

$$\gamma = \tan^{-1}\omega rC. \tag{2.24}$$

Thus the mean value of the steady-state current passing through the fluid is

$$\bar{i}_{ac}{}^{\infty} = \frac{2V_0(R+r+Rr^2C^2\omega^2)}{\pi[(R+r)^2 + R^2r^2C^2\omega^2]} \tag{2.25}$$

and the mean value of the steady-state power consumed by the ER fluid is:

$$\overline{P}_{ac}{}^{\infty} = \frac{rV_0{}^2}{2[(R+r)^2 + \omega^2R^2r^2C^2]}. \tag{2.26}$$

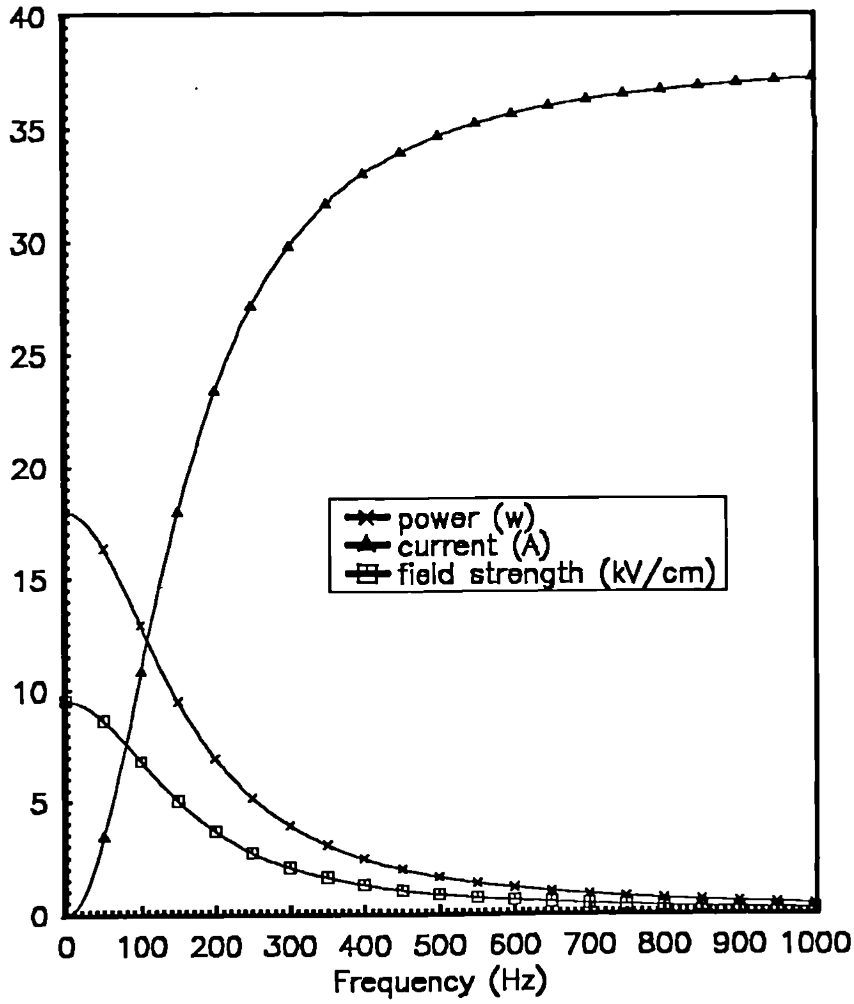

Figure 2.6: The influence of frequency on field strength, current and power

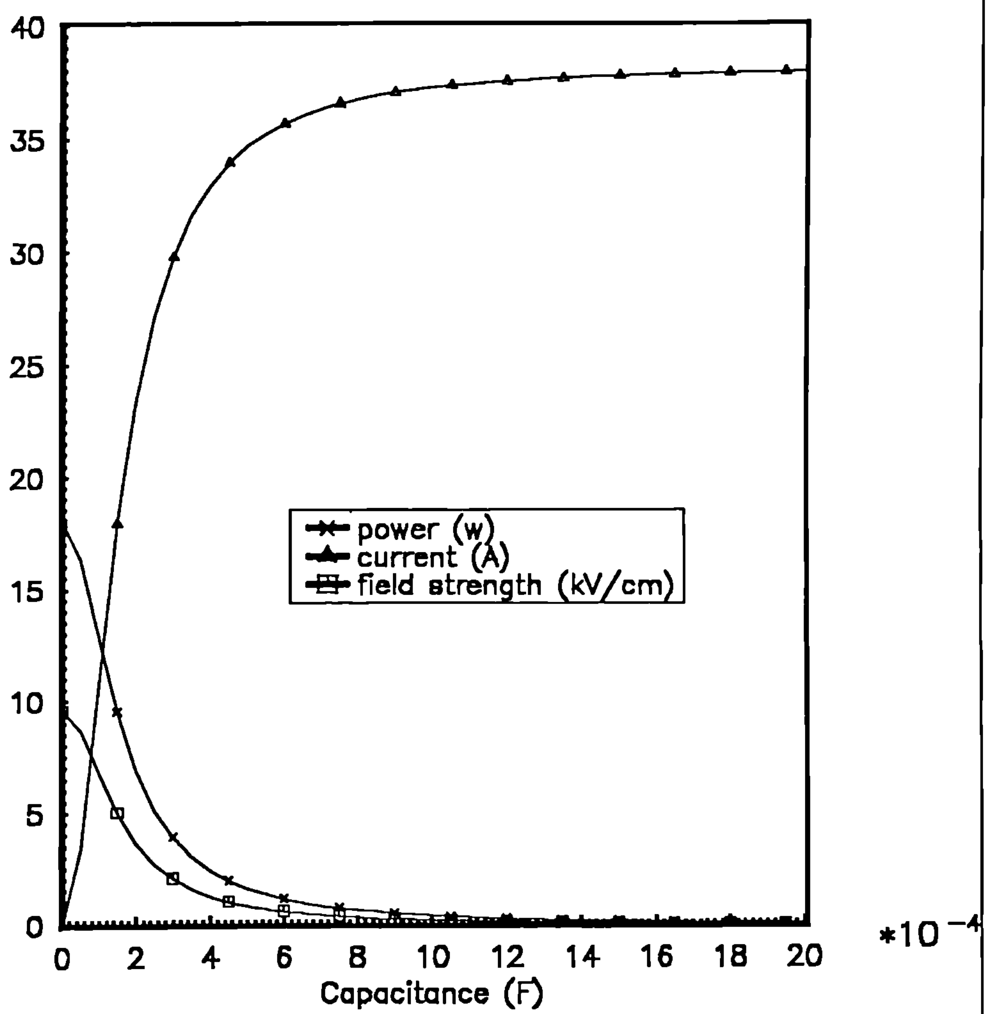

Figure 2.7: The influence of capacitance on field strength, current and power

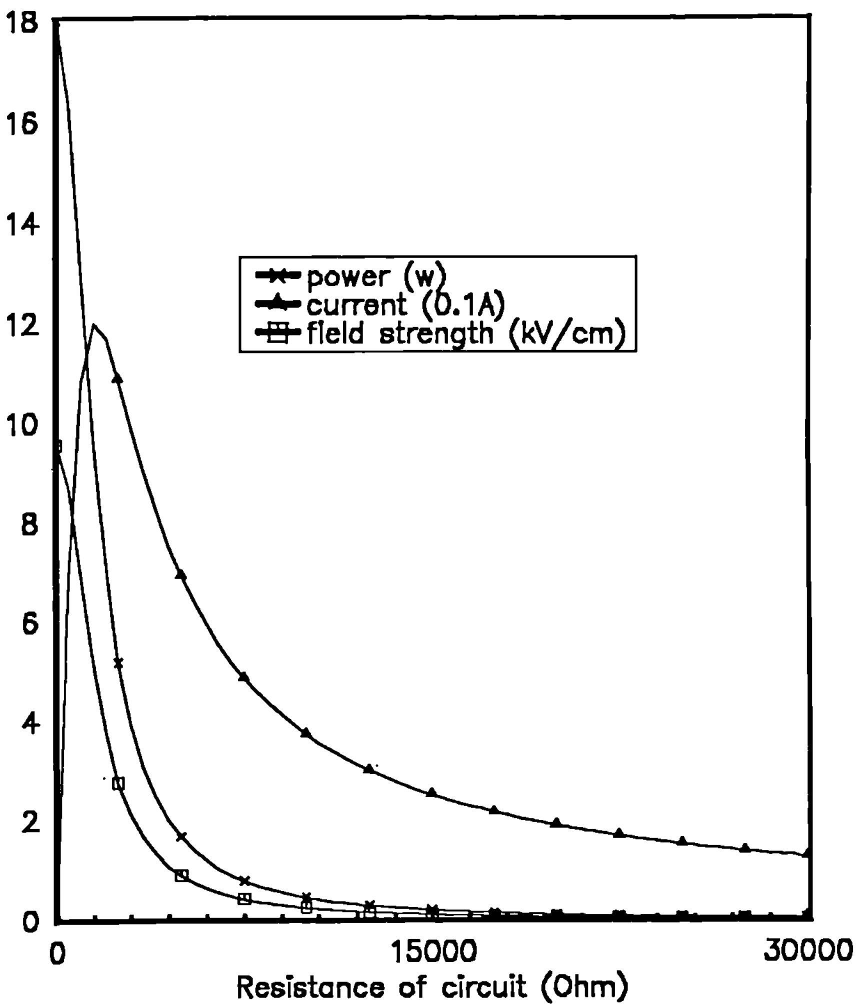

Figure 2.8: The influence of circuit resistance on field strength, current and power

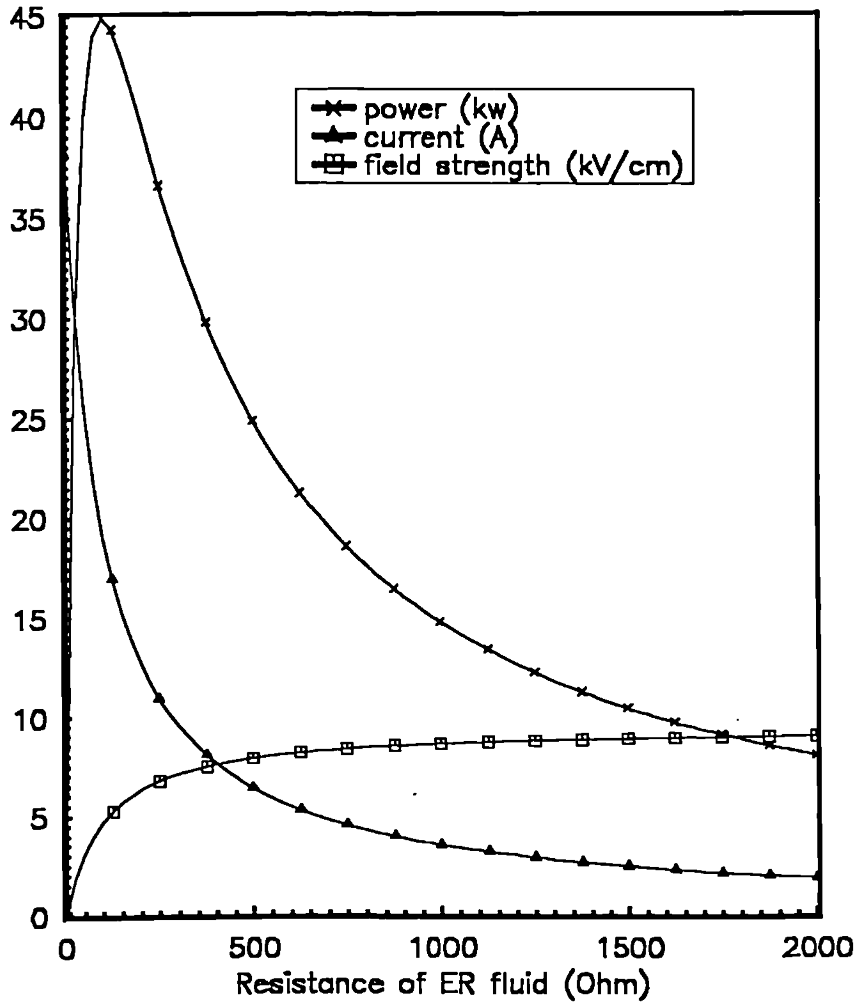

Figure 2.9a: The influence of ER fluid resistance on field strength, current and power

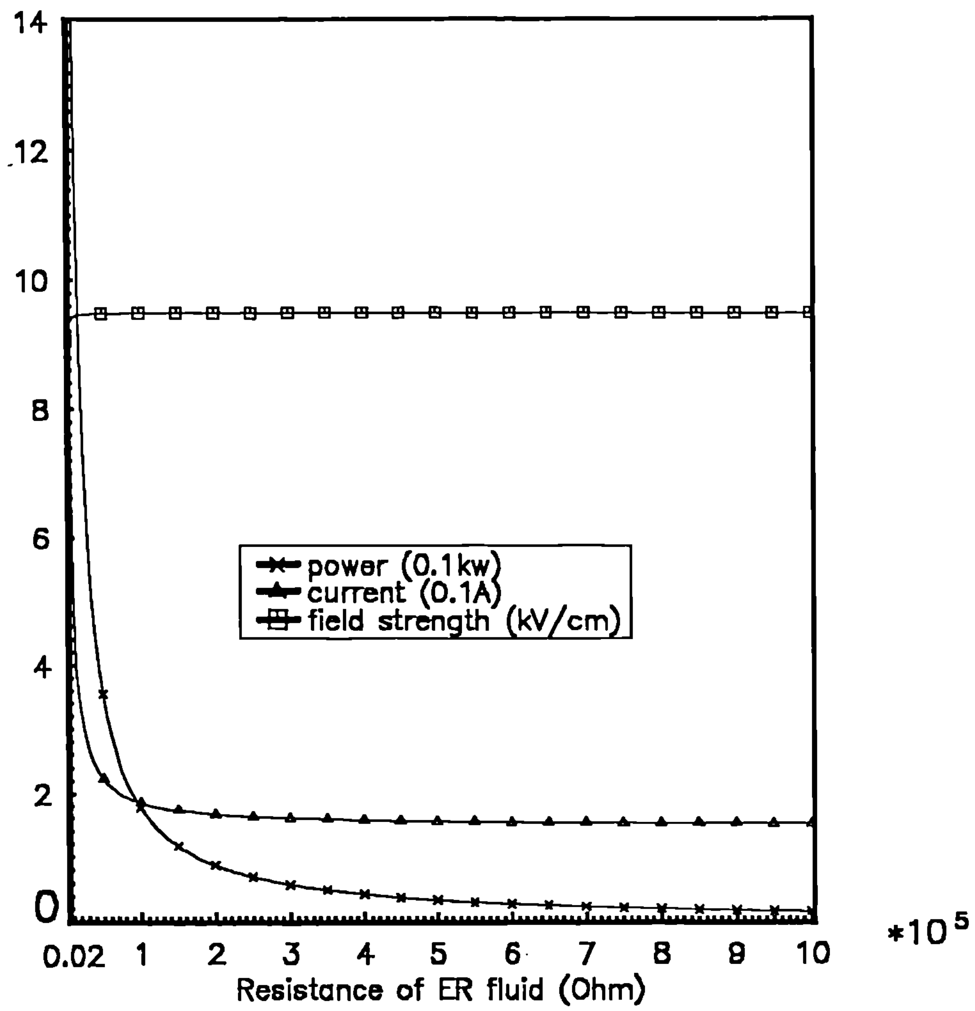

Figure 2.9b: The influence of ER fluid resistance on field strength, current and power

The above analysis shows that no matter whether the ER fluid is conducting or non-conducting, the frequency of the power source has the same influence on the ER effect. As can be seen from equations (2.16) and (2.22) the increase in frequency will lead to a decrease in the mean value of steady-state field strength which is essential for the ER effect. Maximum field strength will be achieved at zero frequency, i.e. a DC field has the best effect on field strength. However, the mean value of steady-state current passing through the ER fluid reaches a minimum at zero frequency, and increases with increasing frequency, until a maximum value is reached, as expressed in equations (2.18) and (2.25). The steady-state mean value of power consumed by the ER fluid clearly decreases with increasing frequency. The dependence of the mean values of steady-state field strength, current and power on frequency is shown in Figure 2.6. It is interesting to find that capacitance (or permittivity) has a similar influence on the ER effect as frequency and this is shown in Figure 2.7.

Figure 2.8 shows the dependence of the mean values of steady-state field strength, current and power on circuit resistance. It is clear that increasing circuit resistance leads to a decrease in field strength and power consumed by the fluid. But there exists a resistance where the current passing through the fluid is maximum, the current increases with increasing resistance before this point and decreases with increasing resistance after this point. As shown in Figure 2.9 (a) and (b), the influence of ER fluid resistance on the ER effect under AC excitation is similar to that under DC excitation.

2.7 A Comparison of DC and AC Fields on the ER Effect

The comparison is based on the model shown in Figure 2.1b. Suppose a DC voltage which corresponds to the mean value of the AC voltage, that is $\mathcal{E} = \frac{V_0}{\sqrt{2}}$, is alternatively applied on the same ER device, then the comparison between DC field strength and AC field strength yields:

$$E_{dc}^{\infty} = \frac{V_0}{\sqrt{2}\, d(\frac{R+r}{r})} > \bar{E}_{ac}^{\infty} = \frac{2V_0}{\pi d(\frac{r+R}{r} + \frac{R^2\omega^2C^2r}{R+r})} \tag{2.27}$$

with the maximum mean value of steady-state AC field strength given by:

$$\bar{E}_{ac}^{\infty} = \frac{2V_0}{\pi d(\frac{R+r}{r})} \tag{2.28}$$

when $\omega \to 0$. This means that a DC signal produces a more effective field than that of an AC signal. The comparison of the current passing through the ER fluid shows that the steady-state DC current is larger than the mean value of the steady-state AC current at zero frequency, but smaller than that when frequency is over a certain range, that is:

$$(\bar{i}_{ac}^{\infty})_{\omega\to 0} = \frac{2V_0}{\pi(R+r)} < i_{dc}^{\infty} = \frac{V_0}{\sqrt{2}\,(R+r)} < (\bar{i}_{ac}^{\infty})_{\omega\to\infty} = \frac{2V_0}{\pi R} \tag{2.29}$$

The comparison between power consumed yields:

$$P_{dc}^{\infty} = \frac{V_0^2 r}{2(R+r)^2} \geq \bar{P}_{ac}^{\infty} = \frac{rV_0^2}{2[(R+r)^2 + \omega^2R^2r^2C^2]} \tag{2.30}$$

The maximum AC power is at zero frequency and has the same value as that of steady-state DC power.

2.8 The Power Needed to Control an ER Device

From the above analysis, for an ER device with perfect dielectric fluid and supplied with a DC voltage, when the charging process is finished, the fluid will not consume any more energy. If the ER fluid is conducting and has a resistance of r, it follows that the power needed to maintain the ER system is given by:

$$P_t = i_{dc}^{\infty}\mathcal{E} = \frac{\mathcal{E}^2}{(R+r)} \tag{2.31}$$

If an AC voltage is applied to an ER device, a charging and discharging process takes place. Taking a conducting ER fluid as an example, the instantaneous steady-state power is:

$$P_t^{\infty} = i_{ac}^{\infty} V_0 \sin \omega t = \frac{V_0^2\sqrt{1 + r^2C^2\omega^2}}{\sqrt{(R+r)^2 + R^2r^2C^2\omega^2}} \sin(\omega t - \beta + \gamma) \sin \omega t \tag{2.32}$$

The mean value at steady state yields:

$$\overline{P}_t^{\infty} = \frac{V_0^2(R + r + \omega^2r^2C^2R)}{2[(R+r)^2 + R^2r^2C^2\omega^2]} \tag{2.33}$$

It is noted that the power needed to control an ER device is a minimum when the frequency $\omega \to 0$, and increases with increasing frequency until a maximum value is reached when $\omega \to \infty$. This is shown in Figure 2.10. Therefore, it takes less power to control an ER device with DC power than with AC power. The capacitance and the resistance of the ER fluid and circuit also influence the power.

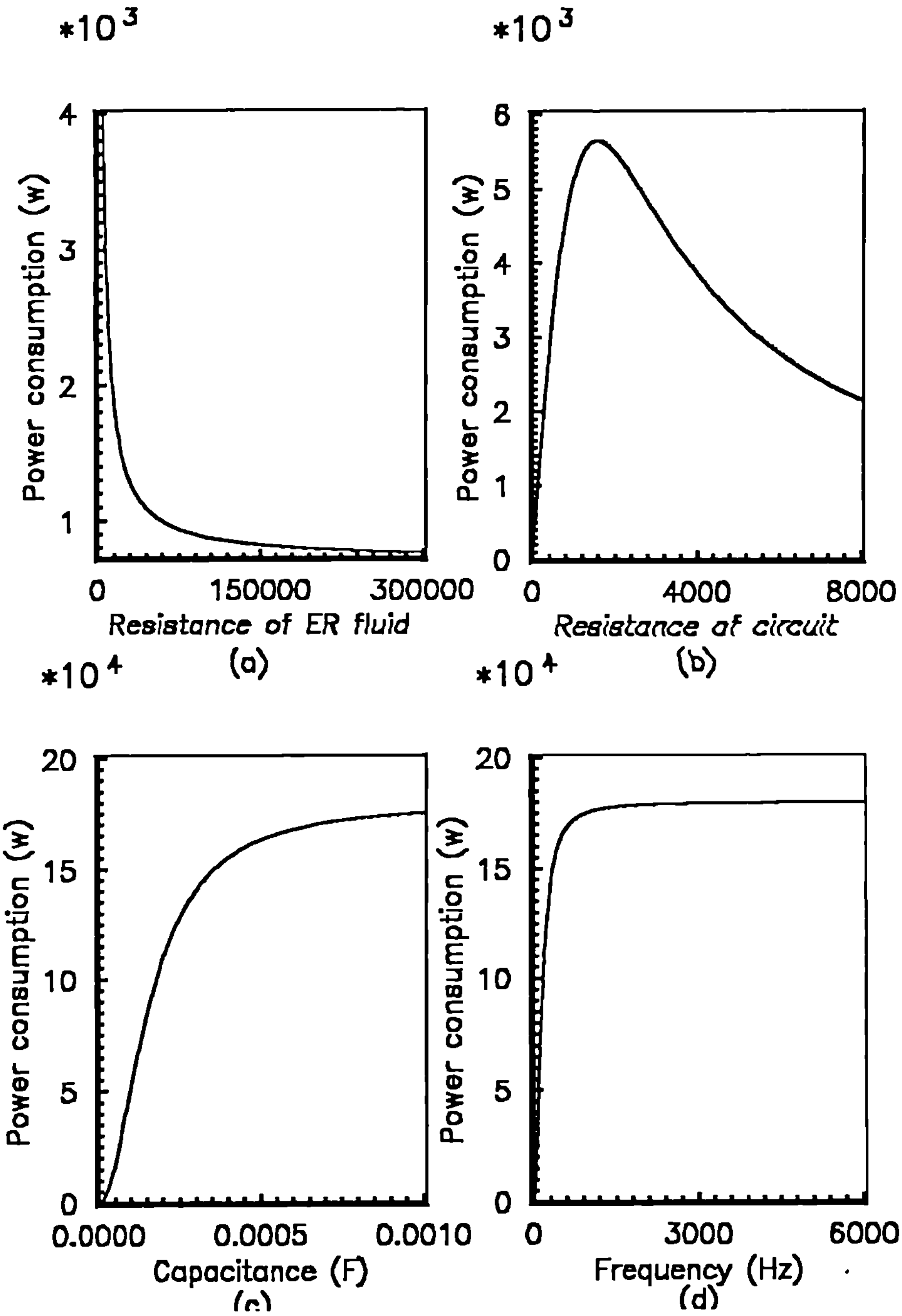

Figure 2.10: ER system control power dependence on fluid resistance, circuit resistance, capacitance and frequency

2.9 The Influence of Current and Temperature on the ER Effect

Usually, when talking about the ER effect, the electric field strength applied to the fluid is generally thought to be responsible for the increase of apparent viscosity: emphasis is not placed on the influence of current on the ER effect. There are two types of parameter which influence the current. One type is the ER system itself, i.e., ER fluid parameters and circuit parameters which have been discussed in the previous Sections. The other is temperature. Some previous work [11,23] showed that the apparent viscosity of some liquids under the application of an electric field increases with increasing current passing through the liquid. This leads to the conclusion that non-conducting liquids do not exhibit the ER effect.

On the other hand, it is well known that an increase of temperature leads to a decrease in liquid viscosity. However, some previous researchers [88,110] found that when the temperature of an ER fluid increases, the torque transmitted by the fluid at higher constant field strength also increases. This result was confirmed by Stevens [88] and an example of this effect is shown in Figure 2.11. The increase in torque is brought about by an increase in the apparent viscosity. It is observed and expected that the increase in temperature not only causes an increase in current which possibly benefit the ER effect, but also a decrease in liquid viscosity (see Chapter 3). This explains how the transmitted torque decreases at lower constant field strength as shown in Figure 2.11. In fact, the torque transmitted is the combination of pure viscous torque and pure ER torque. It seems appropriate to assume that the increase in current helps to increase the ER effect.

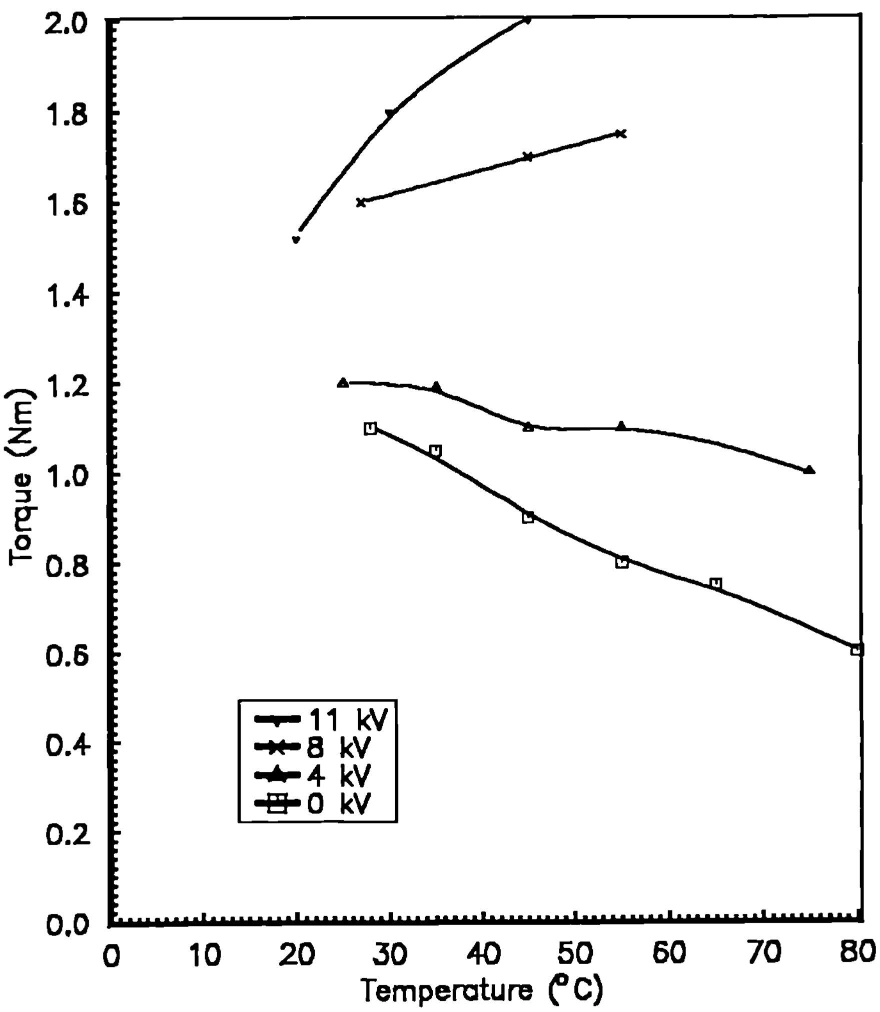

Figure 2.11: Temperature influence on torque transmission

However, a significant current is a disadvantage for practical applications, since:

1. The increase in current causes an increase in heat generation in the ER fluid.

2. The increase in current causes an easier breakdown in the ER effect.

3. The increase in current produces an increase in the power consumption from the high voltage generator

4. The increase in current increases the possibility of electrocution

Therefore, these are drawbacks in trying to increase the ER effect by increasing the current passing through the ER fluid.

Furthermore, it can be deduced that the power consumed by the ER fluid is also beneficial to the ER effect, because both current passing through the fluid and the voltage applied to the fluid help to enhance the effect. However, power itself cannot be a parameter which can be used to judge the ER effect, due to the fact that voltage and current do not have the same level of influence on the ER effect. Voltage may have a more obvious influence on the ER effect. Hence it is suggested that a high electric field strength with a reasonably large power consumption by the ER fluid could help produce the best ER effect.

2.10 Summary of Chapter 2

From the above theoretical analysis, the following can be concluded:

1. The magnitude of the ER response time is proportional to both circuit resistance and fluid permittivity. Thus to achieve a fast responsive ER system, it is necessary to reduce the circuit resistance and fluid permittivity.

2. The electric field strength applied across the ER fluid decreases with increasing circuit resistance, field frequency and system capacitance, but increases with fluid resistance.

3. The current passing through an ER fluid decreases with increasing fluid resistance, circuit resistance (DC case), but increases with field frequency and system capacitance. However, in the AC case, there exists an optimum value of circuit resistance, below which the current increases with circuit resistance and then decreases.

4. The electrical power consumed by the ER fluid decreases with increasing circuit resistance, field frequency and system capacitance. However, there exists an optimum value of the fluid resistance, below which the power increases with fluid resistance and then decreases.

5. The electric power needed to control and operate an ER system generally increases with capacitance and field frequency but decreases with fluid resistance. There exists an optimum value of the circuit resistance below which the power increases with circuit resistance and then decreases.

CHAPTER 3

ELECTRORHEOLOGICAL POWER TRANSMISSION

3.1 Introduction

The Newtonian law of fluid shear is long established and its principle has been widely used in the study of hydrodynamic bearing systems. However, it was not until the end of the 1950's and the early 1960's that the theory was applied in a power transmitting device, the Hydroviscous Drive (HVD) [5]. The HVD is a device in which power is transmitted from the driving part to the driven part through the action of the viscous shear stress in the intervening thin oil film. The oils used as the power transmission medium have a fixed viscosity at constant temperature. In order to achieve a continuously variable output torque and speed, the thickness of the oil film or the effective working area between the driving part and the driven part has to be changed by some means. Although an HVD has a wide range of applications in heavy industries, for example, in variable speed pumps and fan drives in power plant and oil transportation, it still has some drawbacks, namely a complicated mechanical structure and control system.

In principle, if the oil in an HVD were to be replaced by an ER fluid, there would need to be no mechanical movement to obtain continuously variable features. By imposing an ER fluid between the driving and the driven parts, which also act as electrodes, it is possible to obtain continuously variable transmission of power simply by varying the voltage applied to the fluid. The feasibility of achieving control of transmitted torque and speed in this way has been demonstrated experimentally with some simple devices [78-80]. Results using laboratory apparatus showed that transmitted torque increased with electric field strength.

Due to the features of ER couplings, many potential applications can be developed. One application involves an ER coupling used as a continuously variable speed cooling fan drive for vehicles. Conventionally, a mechanical fan drive is used in a vehicle cooling system, in which the output speed of the fan is the same as the speed of the engine fan drive shaft. This means energy is dissipated even when engine cooling is not required. In addition, extra noise is generated. A magnetic fan drive was found to be better than a mechanical one. Later, the viscous fan drive, in which the speed of the fan is regulated by the temperature controlled viscous shear stress, began to be used on many commercial vehicles [111]. A successful ER fan drive could be used to replace the above three.

ER devices can also be used for other power transmission purposes, for example, to form a continuously variable speed drive shaft. Potential applications are ER brakes and dynamometers. All these possible applications are studied theoretically and experimentally in this chapter.

One of the problems encountered in variable speed transmission devices is the significant temperature rises, especially during conditions of continuous slip. ER couplings also have a similar problem. There are two basic mechanisms by which heat is generated in ER couplings:

1. an electrical heating effect due to the current;

2. mechanical heating due to the slippage between the input and output parts of the ER coupling.

The electrical heating effect has been discussed in section 2.5. The mechanical effect will be discussed in this Chapter. Also the influence of temperature on the power transmission characteristics of ER devices is considered.

Results show that it is feasible to employ a single plate ER coupling as a brake and as a dynamometer. Temperature is shown to be helpful to the ER effect. An ER fan drive is shown to provide a continuously variable output speed, although the variable range is limited because of the poor shear property of the fluid used. A multiplate ER drive shaft is shown to be capable of providing variable output speeds over a wide range and including direct transmission. Various aspects related to the mechanical design of ER power transmission devices are also discussed in this Chapter.

3.2 Theoretical Background

In the solution of some fluid problems, the viscosity of the fluid can be neglected for mathematical convenience and often a satisfactory result can be obtained. However in other problems, viscosity plays a very much more important role in determining the fluid flow characteristics. The latter is true for the hydroviscous drive and the electrorheological coupling. As indicated in Section 2.2, apparent viscosity is the most convenient parameter to represent the state of an ER fluid. Hence viscous flow theory will be used to model the flow of an ER fluid. Although an ER fluid does not strictly behave like a Newtonian fluid when electrically stressed, it may behave like a Newtonian fluid when little or no electric field is applied. Thus the analysis of viscous flow, confined to the case of incompressible, homogeneous, Newtonian fluids with constant viscosity and density, can help in understanding the characteristics of ER power transmission.

3.2.1 Plane Flow

We begin by examining an idealised model of a plate-type device. A plate-type ER device can be represented by the diagram shown in Figure 3.1, where relative velocity exists between the two plates. The following assumptions are then made:

1. The fluid thickness h is very small in relation to the length and width x and z.

2. There is no pressure difference across the fluid, i.e., $\frac{\partial p}{\partial y} = 0$.

3. The flow is laminar and there is no motion in the y and z directions, that is, v=0 and w=0.

4. There is no external force acting on the oil film, that is, $F_x = F_y = F_z = 0$.

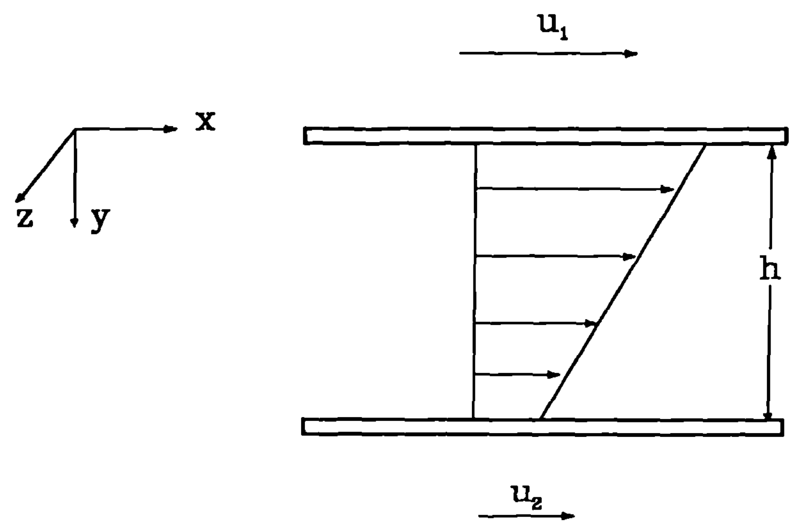

Figure 3.1: Fluid flow between two plates

5. The inertia of the fluid is very small compared with the viscous shear stress and therefore $\frac{Du}{Dt} = \frac{Dv}{Dt} = \frac{Dw}{Dt} = 0$

Thus the velocity distribution can be derived in the usual way from the Navier-Stokes equation[112] as:

$$u = \frac{\partial p}{\partial x} \frac{y(y-h)}{2\mu} - \frac{u_1(y-h)}{h} + \frac{u_2 y}{h}. \tag{3.1}$$

This yields:

$$\tau_x = \mu \frac{\partial u}{\partial y} = \frac{(2y-h)(\partial p/\partial x)}{2} + \frac{\mu(u_2 - u_1)}{h} \tag{3.2}$$

Having examined a plate-type model, we will proceed to examine a cylindrical-type model.

3.2.2 The Flow Between Two Rotating Concentric Cylinders

Consider two very long concentric cylinders, as shown in Figure 3.2, which are rotating at different angular speeds. The flow between the cylinders results in $u_r = 0, u_z = 0$. Thus the shear stress between is given by

$$\tau_{r\phi} = \frac{2\mu(\omega_2 - \omega_1){r_1}^2{r_2}^2}{({r_2}^2 - {r_1}^2)r^2} \tag{3.3}$$

The shear torque on the cylinders of length L is then

$$T_1 = -T_2 = \frac{4\pi\mu(\omega_2 - \omega_1){r_1}^2{r_2}^2}{{r_2}^2 - {r_1}^2} L \tag{3.4}$$

3.2.3 Cylindrical ER Coupling

The configuration of the cylindrical ER coupling is shown in Figure 3.3. The torque is transmitted through a multi-cylinder arrangement where the ER fluid is contained in the annuli between the cylinders. This type of configuration for ER couplings is particularly suitable for small power and space-limited applications, such as variable speed vehicle fan drives [111].

Suppose that the input angular speed is ω_1, the output angular speed is ω_2, and dimensions are as shown in Figure 3.3. Then the torque transmitted by m cylindrical surfaces is:

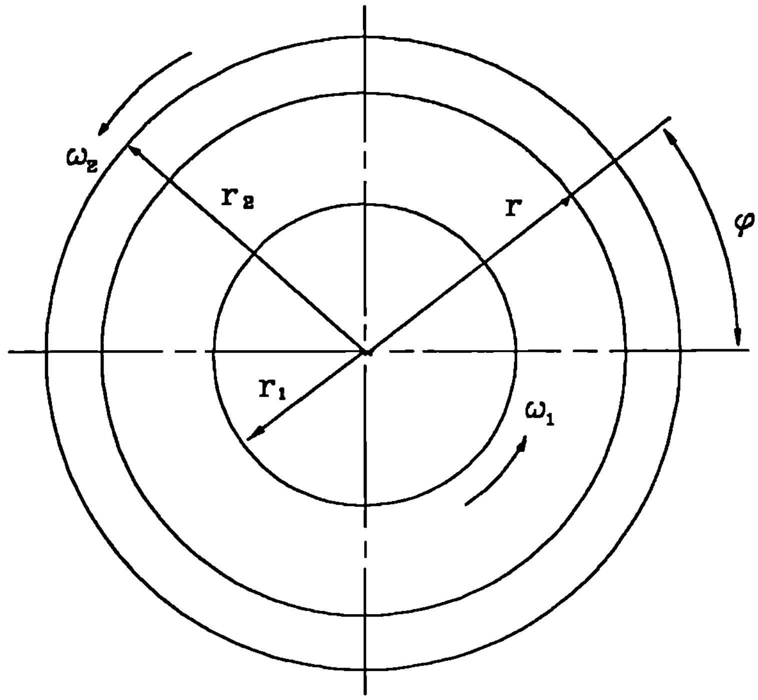

Figure 3.2: Fluid flow between two concentric cylinders

$$T = \sum_{k=1}^{m} \frac{4\pi\mu(\omega_2 - \omega_1)(r_{2k+1}r_{2k+2})^2}{(r_{2k+2})^2 - (r_{2k+1})^2} L \qquad (3.5)$$

When such a device is built and ER fluid is chosen, the mechanical variables in equation (3.5) are T and $\Delta\omega = \omega_2 - \omega_1$. However it should be noted that by changing the electric field applied to the ER fluid, the apparent viscosity

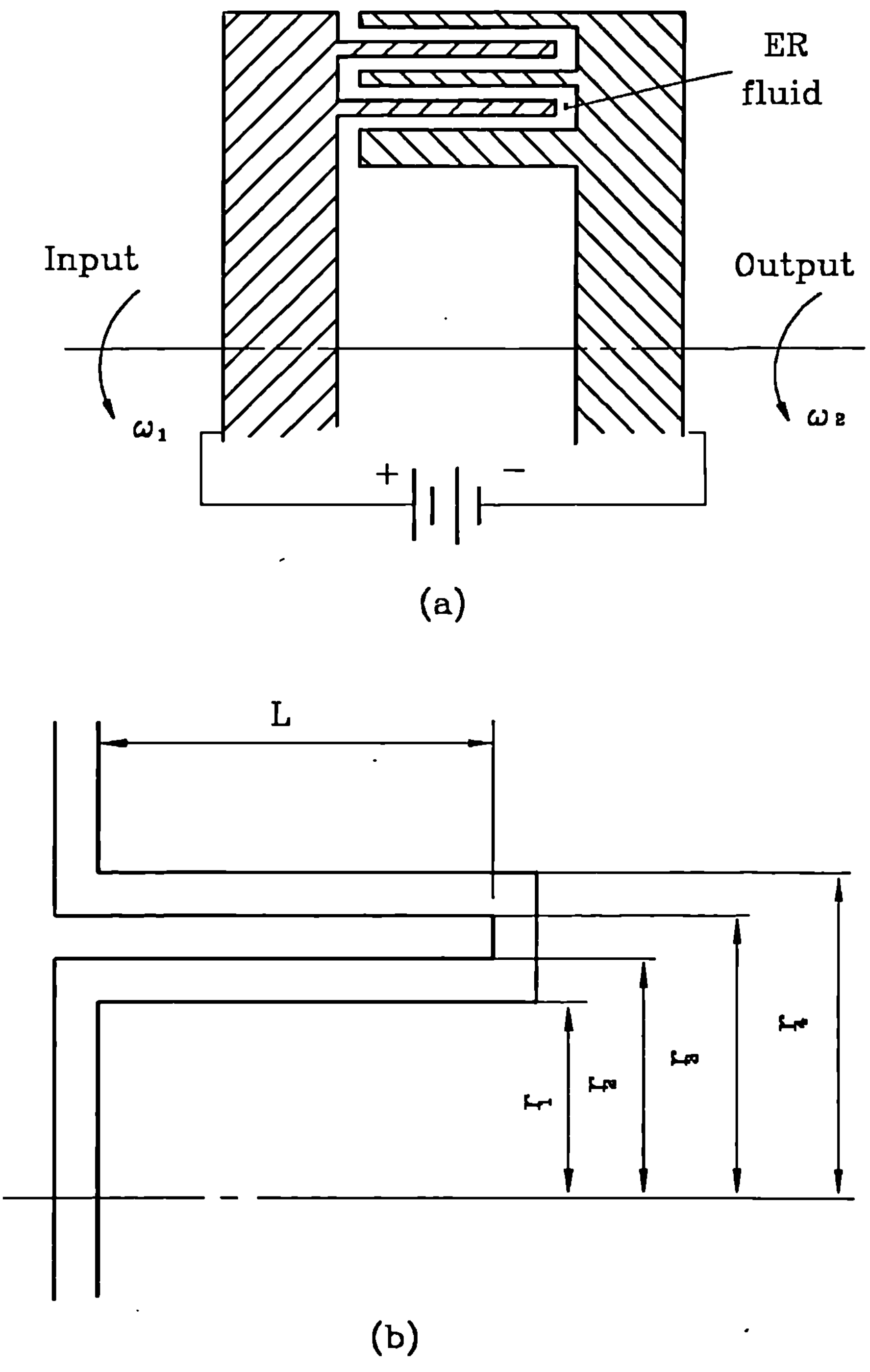

Figure 3.3: Schematic of a cylindrical ER coupling

of the fluid, μ, is also variable. This is actually the way used to regulate an ER device.

3.2.4 Plate Type ER Coupling

Multiplate ER couplings, which have similar configurations to hydraulic clutches, can be used, for example in pumps, fans and blowers which operate under variable speed conditions, and especially in heavy power applications. For convenience of solution, the plane flow is used to approximate the flow between two plates as shown in Figure 3.4. Furthermore, because of symmetry of the plate, $\frac{\partial p}{\partial \phi}$ (corresponding to $\frac{\partial p}{\partial x}$ in equation (3.1)) can be considered to be negligible. Thus the torque transmitted across m working surfaces of the ER coupling can be written as:

$$T = \int_{r_1}^{r_2} r\tau 2\pi r dr = \int_{r_1}^{r_2} 2\pi\mu(\omega_2 - \omega_1) r^3 dr \tag{3.6}$$

that is

$$T = \frac{m\mu\pi(\omega_2 - \omega_1)}{2h}(r_2{}^4 - r_1{}^4) \tag{3.7}$$

It is clear that torque T can be regulated either by changing the gap h, speed difference $\Delta\omega$, or the viscosity of the ER fluid. In practice, in order to meet different power needs, it is the apparent viscosity to be regulated by changing the applied electric field.

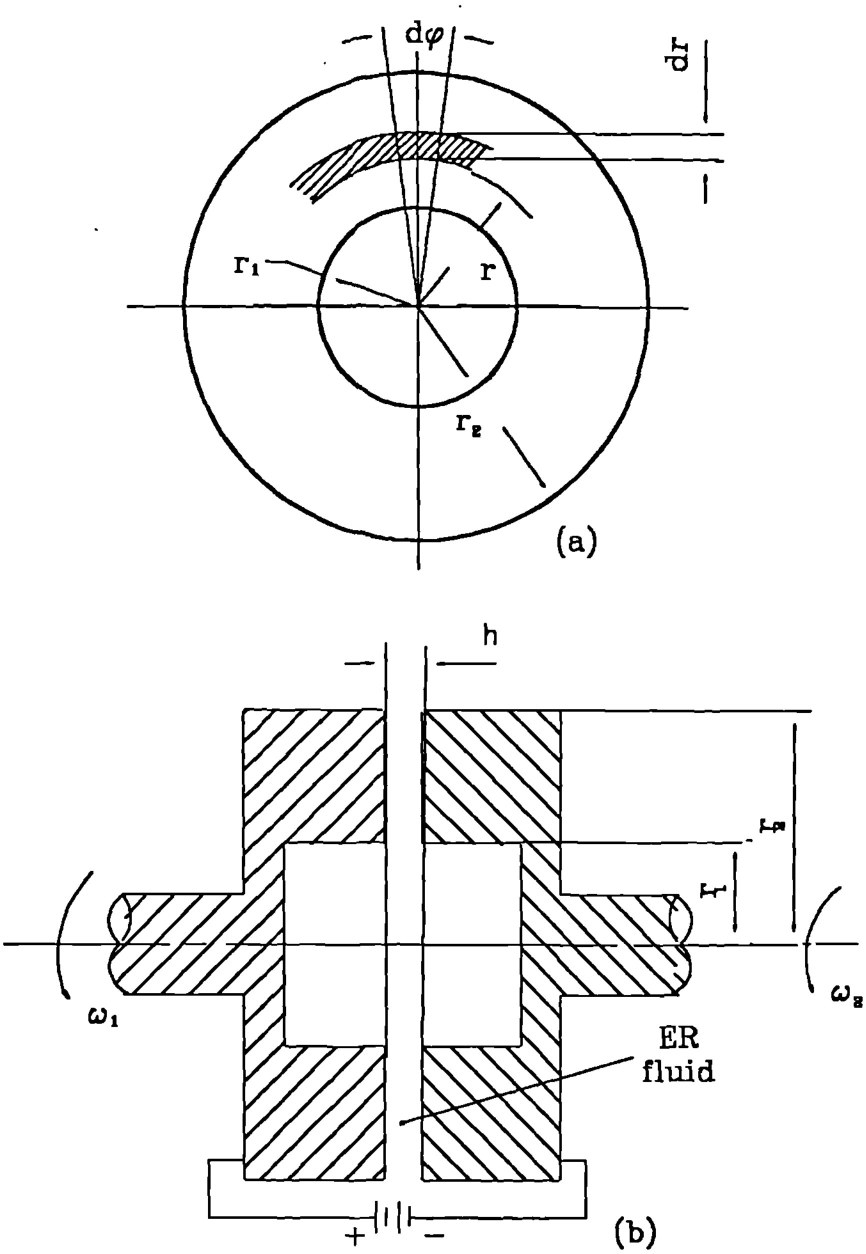

Figure 3.4: Schematic of a plate type ER coupling

3.2.5 Characteristics of ER Power Transmission

In order to study the characteristics of ER couplings, it is convenient to consider a general case, say plate type, for a constant gap h and a certain configuration. Equation (3.7) then becomes:

$$T = C\mu\Delta\omega \tag{3.8}$$

Thus the following characteristics can be obtained.

A. Load: When the apparent viscosity of the ER fluid is constant, that is the electric field is constant, the load torque T is proportional to the speed difference $\Delta\omega$, i.e. inversely proportional to speed ratio i when input speed is fixed. This is shown in Figure 3.5. Thus it appears that when the input speed is constant, the output speed ω_2 can automatically change to match the load torque T. Thus when the imposed load increases, the output speed will decrease to meet load requirement and when the load decreases, the ER coupling will produce a gain in output speed. This is only true for those loads which monotonically decrease with speed. For those which monotonically increase with speed, there would have to be a control system for modulating the electric field.

Load T is also proportional to the apparent viscosity of the ER fluid. Furthermore, the ER coupling provides the characteristics of constant speed and constant torque modes, shown as line DB and line EC in Figure 3.5.

To conclude, if any two of the three parameters T, $\Delta\omega$ and μ are determined, the remaining performance can be evaluated.

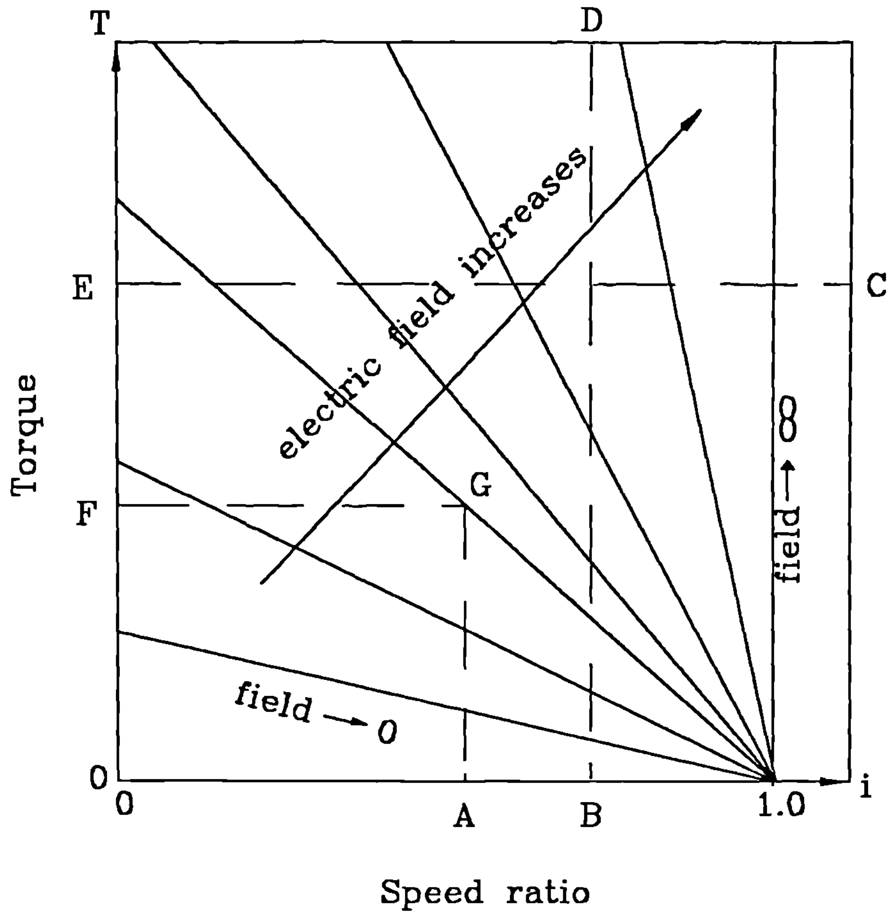

Figure 3.5: Characteristic of ER couplings

B. Efficiency: The efficiency η, is defined as the ratio of the output power to the input power,

$$\eta = \frac{N_2}{N_1} = \left| \frac{T_2 \omega_2}{T_1 \omega_1} \right| = \left| \frac{-T_1 \omega_2}{T_1 \omega_1} \right| = i_{21} \qquad (3.9)$$

It follows that the efficiency of the ER coupling is equal to its speed ratio. In practice, however, the magnitude of the output torque is a little smaller than that of the input torque because of friction and thus efficiency is also a little smaller than speed ratio. It is noted that for small speed ratios, the ER coupling has a poor efficiency. This implies that the ER coupling has the same efficiency characteristic as a hydraulic coupling.

3.2.6 ER Coupling Saves Energy

Variable speed power transmissions, such as the hydraulic coupling and the hydroviscous drive, have proved to be efficient in saving energy in applications, such as speed regulating fans, blowers and pumps, where a throttling system has been previously applied. This is also true for ER couplings. Figure 3.6 shows an example of such an application, in which an ER coupling is used to regulate the speed of a fan or pump. For centrifugal fans and pumps, which are popularly used in industry, the relationship between torque and speed is approximately:

$$T_2 = C{n_2}^2 \tag{3.10}$$

where C is a constant determined by the physical characteristics of the device, and n_2 is the rotational speed of the fan or pump. Thus the energy wasted because of slippage is:

$$N_s = N_1 - N_2 = T_1\omega_1 - T_2\omega_2 = 2\pi n_1 T_1(1 - i_{21}) = 2\pi C(1 - i_{21}){n_1}^3{i_{21}}^2 \tag{3.11}$$

Differentiating N_s with respect to i_{21}, it can be seen that N_s is maximum when $i_{21} = 2/3$. It then follows from (3.11) that

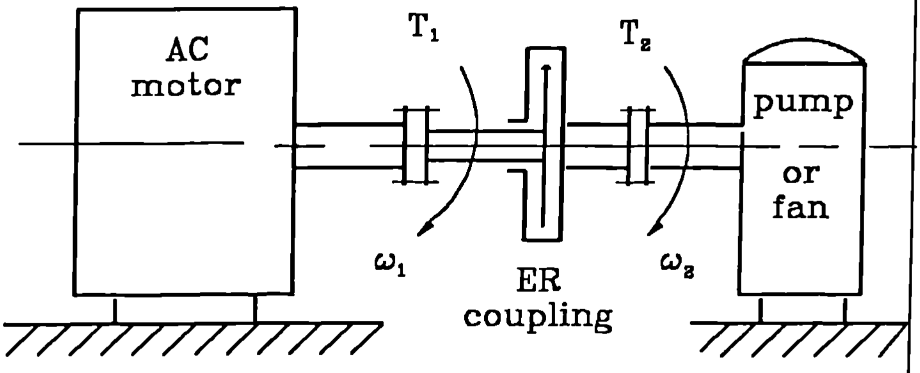

Figure 3.6: An ER coupling used as a speed regulator

$$\frac{(N_s)_{max}}{(N_1)_{max}} = \frac{2\pi C n_1^3 (1 - \frac{2}{3})(\frac{2}{3})^2}{2\pi C n_1^3} = 14.8\ \% \qquad (3.12)$$

Hence, when $i_{21} = 2/3$, the ER coupling wastes 14.8% of the A.C. motor's full power. This is a very small figure compared to that wasted in a throttling system, as shown in Figure 3.7. Area B represents the energy dissipated in regulating the output speed of the ER coupling and area A represents the energy saved by the ER coupling compared with throttling regulation in fan and pump applications. It should be noted that the maximum energy wasting condition can be avoided by proper control.

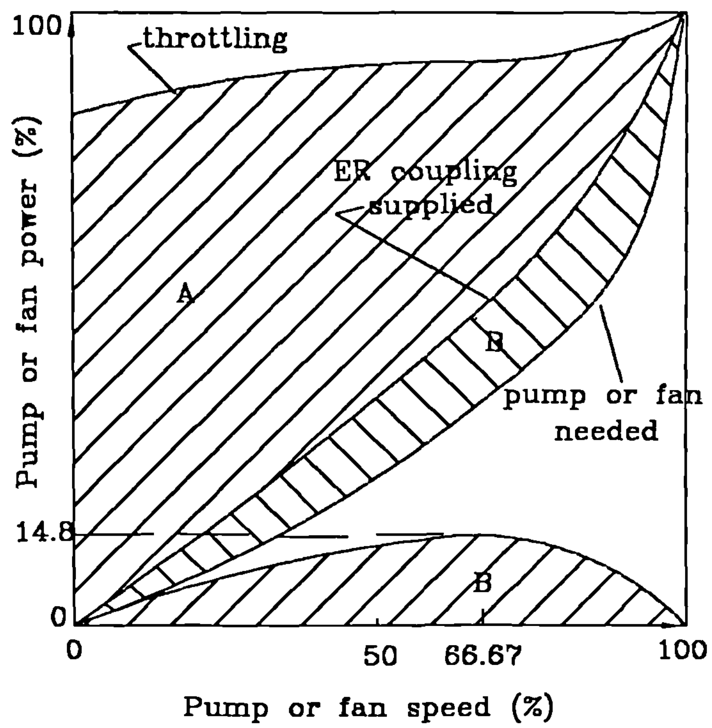

Figure 3.7: Power consumption between throttling and ER coupling

3.2.7 Advantages and Disadvantages of ER couplings

The ER coupling is a new addition to the class of devices used for continuously variable power transmission. Compared with the others, such as hydroviscous drives, hydraulic couplings, hydrodynamic torque converters and variable speed AC motors, the ER coupling has the following advantages:

1. No mechanical movement is needed to achieve a variable output. Thus the structure of the device can be made simpler than conventional couplings.

2. As electric field strength is the only parameter which directly modulates the coupling, it is easier to realise automatic control.

There is no doubt that ER couplings also have their shortcomings, namely:

1. Safety problems associated with the requirement for a high voltage.

2. Particles in the ER fluid may settle down if the device is not used for a long time, and it may not always be possible to agitate the particles by relative motion of the electrodes (plates or cylinders).

3.3 Mechanical Design of ER Power Transmission Devices

The design of an ER coupling involves: (a) arranging suitable insulation between live and earthed electrodes which usually form the driving and driven parts of the coupling; (b) arranging insulation between external components and the live electrode; (c) mechanical sealing of the ER fluid; (d) supplying the high voltage to the live electrode; and (e) choosing the electrode configuration and area.

3.3.1 Insulation Arrangement between Live and Earthed Electrodes

Components made from metallic materials are often necessary in mechanical devices since non-metallic materials either are not strong enough or too expensive to be used on a large scale. Metals are also the main materials for ER devices. Therefore, an insulator has to be used to separate the two electrodes from contact. There are many ways of achieving this.

1. For devices which are used to transmit relatively small amounts of power, a shaft made of insulating material can be used to connect the live electrode. The shaft can then separate the live and earthed electrodes.

2. For devices which are used to transmit larger amounts of power, a shaft made of insulating material may be not sufficiently robust. Therefore electrodes have to be separated by non-metallic materials which act simply as separators and experience no torsional force.

The first is the more simple approach. Two examples are shown in Figure 3.8 and Figure 3.9. In Figure 3.8, the main body of the shaft is made of insulating material, while in Figure 3.9 the insulating shaft is incorporated with metallic material. These arrangements are used in the ER brake and ER fan drive respectively which will be discussed in the experimental section of this chapter.

Figure 3.10 shows the second way of insulation. It is clear that the insulators only sustain a pressure stress, no torsional stress is applied. This arrangement of insulation is used in the design of the drive shaft, in which the live electrode is exposed to the air.

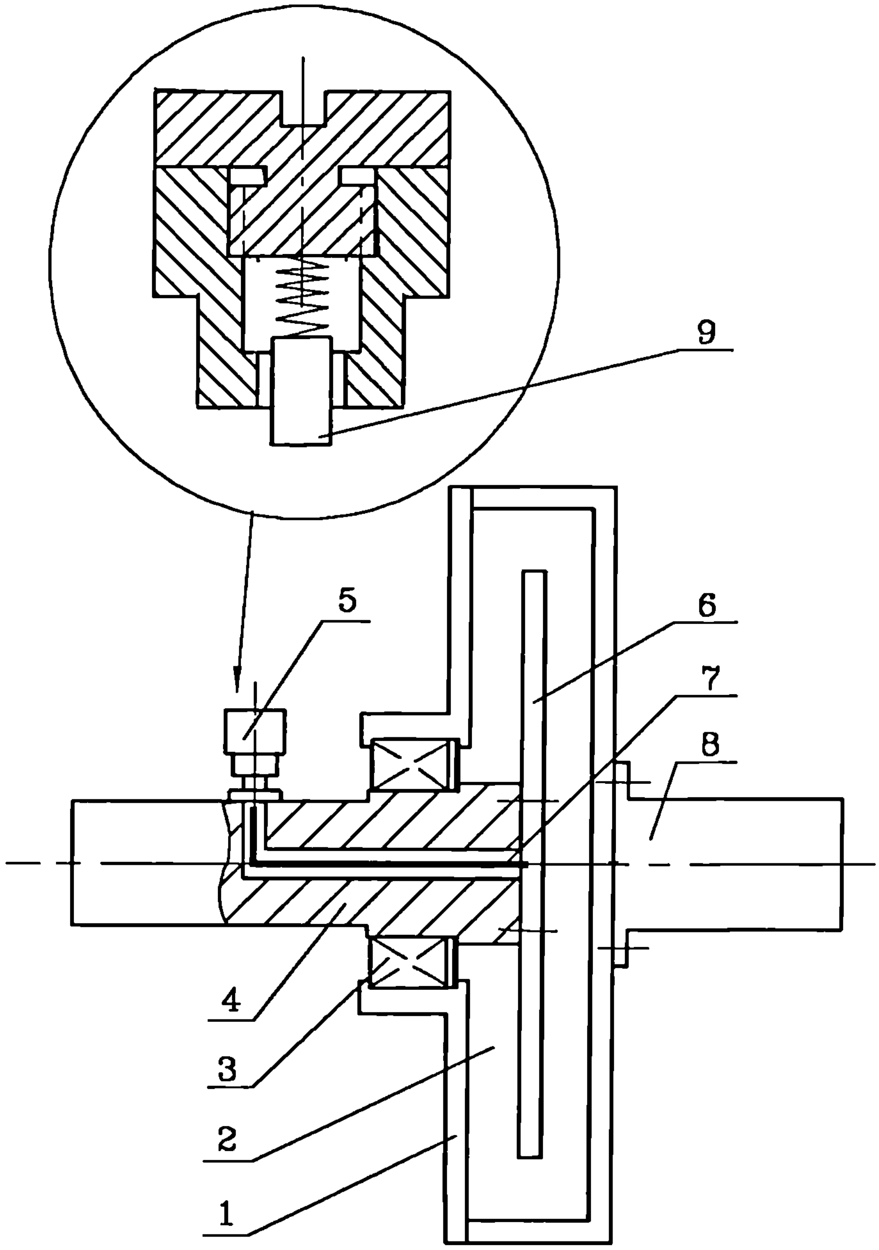

Figure 3.8: An ER coupling arrangement 1. Casing, 2. Fluid chamber, 3. Bearing, 4.Input shaft made of insulator, 5.Electric brush holder, 6.Live plate, 7.Live connection, 8.Output shaft, 9.Carbon brush

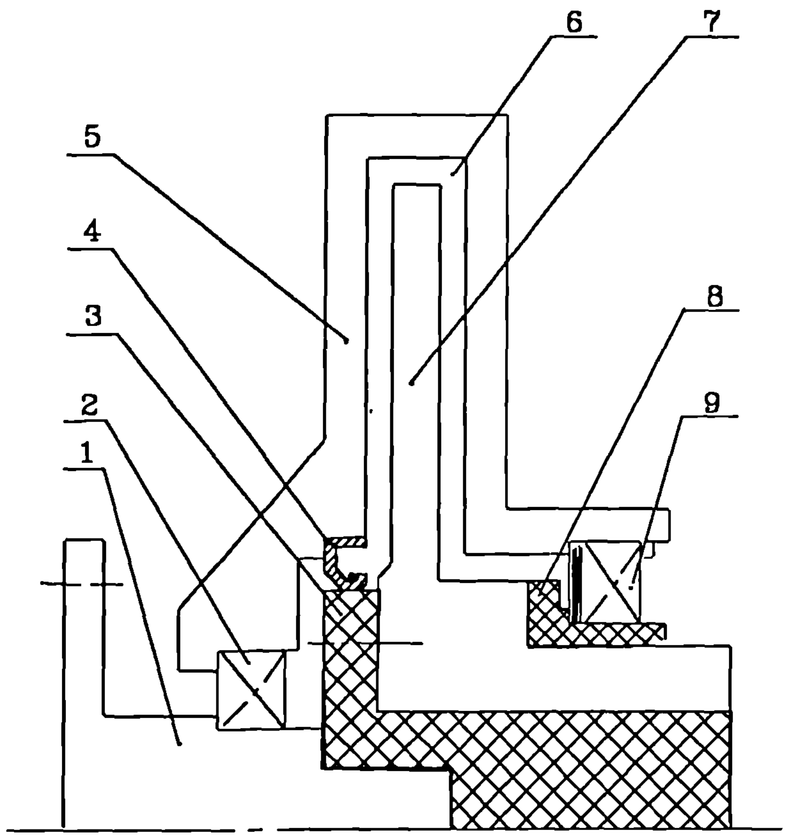

Figure 3.9: An ER coupling arrangement 1.Input shaft, 2.Bearing, 3.Insulator, 4.Lip seal, 5.Casing, 6.Fluid chamber, 7.Live plate, 8.Insulating spacer, 9.Self-sealing bearing

3.3.2 Insulation Arrangement between Live Electrodes and External Equipment

In order to make the structure of the coupling as simple as possible, the insulation arrangement between the two electrodes should take into account the

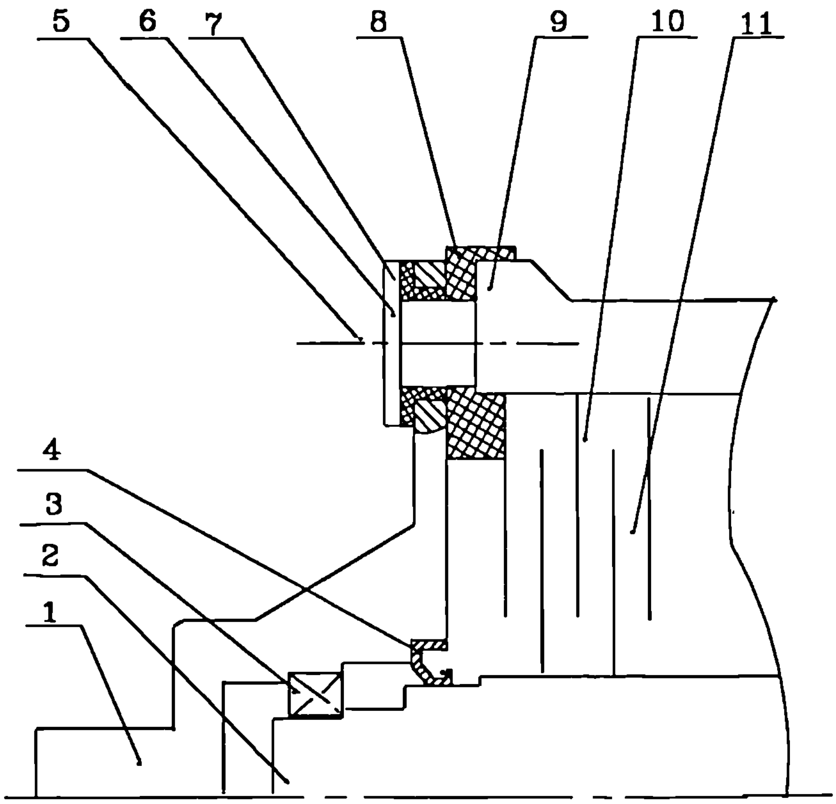

Figure 3.10: An ER coupling arrangement 1.Input shaft, 2.Output shaft, 3.Bearing, 4.Lip seal, 5.Bolt, 6.Buffer, 7,8.Insulating spacer, 9.Casing, 10.Live plate, 11.Fluid chamber

insulation between the live electrode and external components. It is clear from Figures 3.8 to 3.10 that the external shaft connecting the shaft of the ER coupling is not charged by the live electrode.

3.3.3 Sealing Arrangements for ER Couplings

The purpose of sealing in ER devices is to prevent ER fluid leaking out of the working chambers. Also, since some ER fluids can damage the bearings, the other purpose of sealing is to prevent ER fluid reaching the bearings.

There are typically two ways to seal the ER fluid. One is to use self-sealing (sealing-bearing), such as that shown in Figure 3.8. The advantage of this arrangement is simplicity. This method has been successfully used in many viscous fan drives [111]. The other approach to sealing is to use conventional lip seals, as shown in Figures 3.8 to 3.10.

Due to the different dielectric properties of the ER fluid and air, the quality of sealing is very important. It is desirable that working chambers in an ER device should be fully filled with ER fluid, in order to reduce the possibility of dielectric breakdown in air.

3.3.4 High Voltage Arrangement

Most ER power transmission devices involve rotating components. Thus the task of applying high voltages to the live electrode is not necessarily straight forward. The most obvious way to approach this task is to use some form of brush arrangement. There are two possibilities:

1. When the live electrode is covered by another part of the ER coupling, a fixed electric brush is used to apply the high voltage. Figure 3.8 shows one example.

2. When the live electrode or part of it is exposed, a flexible electric brush can be used, as shown in Figure 3.9 and Figure 3.10.

The advantages of the first arrangement are safety, reliability and convenience, whilst the advantage of the second arrangement is simplicity. It is recommended that the second arrangement should only be adopted for use with prototype devices.

3.3.5 The Choice of Electrode Configuration and Area

As discussed in the part 2 of this chapter, there are two configurations which are suitable for ER power transmission devices: plate type and cylindrical type. It is not always easy to specify which configuration is the better for a particular application. The choice mainly depends on conditions like space availability and manufacturing cost.

As shown in equation (3.9), if a plate type configuration is chosen, it is better to make full use of the effective outer diameter of the plates and the number of plates, because transmitted torque increases with these two parameters rapidly. As shown in equation (3.19), if a cylindrical type is chosen, not only should the effective outer diameter and number of the the cylindrical teeth be utilised to the full, but also the length of the teeth. The area of the working chambers can then be the most effective.

The choice of the gap between electrodes usually depends on three parameters, i.e., the original viscosity or shear stress of the ER fluid, the maximum shear stress of the ER fluid and the high voltage available. The original viscosity determines the minimum torque to be transmitted, the maximum shear stress determines the maximum transmitted torque and the maximum voltage determines the maximum electric field strength available. In practice, compromise is necessary between the three parameters.

There are, of course, many other factors which should be taken into account in the design process, such as the cooling of the devices and refilling of the ER fluids.

3.4 An Experiment Involving An ER Brake/Dynamometer

3.4.1 Structure of the ER Brake

The ER brake is actually a coupling with a single pair of plates as shown in Figure 3.11. The driving plate (12), which is immersed in ER fluid, acts as the live electrode. The input shaft (1) is connected to the plate by six bolts. This shaft is mounted in the bearing housing (5) and supported by two rolling bearings. For the sake of insulation, these bearings are not mounted on the metal shaft but on a PTFE separator (6).

High voltage supply is through a brush arrangement consisting of a brass slip ring (3) mounted on the bearing spacer and carbon brush. The carbon brush is embraced in a PTFE brush holder (4). The brush is held in contact with the slip ring by an integrated spring.

The driven part acts as the earthed electrode, which consists of two parts (9) and (13). An 'O' ring seal (10) is incorporated along the edge of the two parts

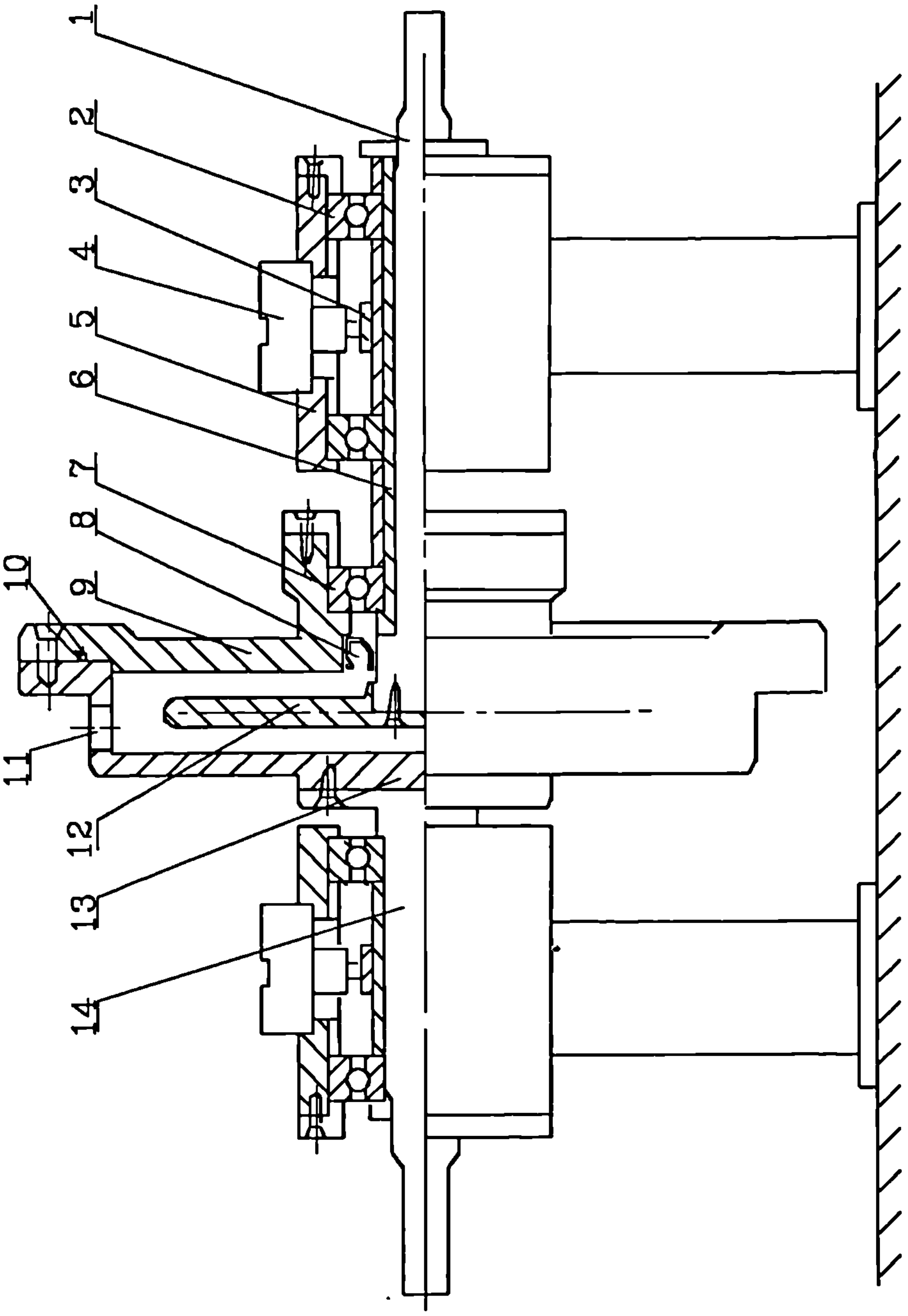

Figure 3.11: An ER brake 1.Input shaft, 2.Bearing, 3.Slip ring, 4.Electric brush holder, 5.Bearing housing, 6.Insulating separator, 7.Bearing, 8.Lip seal, 9.Right-hand casing, 10.'O' ring seal, 11.Refilling hole, 12.Live plate, 13.Left-hand casing, 14.Output shaft

to prevent the ER fluid from leaking. One of them (9) is mounted on the input shaft through a rolling-element bearing which in turn is separated from the input shaft by a PTFE liner (6). The other (13) is bolted to the output shaft (14). The output shaft is in turn mounted on the bearing carrier by two rolling bearings. The brush arrangement on the earth side is similar to that of the live electrode. To retain the fluid in the working chamber, a lip seal (8) is incorporated.

The gap between the electrodes can be altered by changing the thickness of the driving plate. In this experiment only one size of plate was used, i.e., 150 mm in diameter and 8 mm in thickness which provides a gap of 4 mm. For the convenience of changing ER fluid in the chamber, a refilling hole (11) is provided on the edge of the driven part.

3.4.2 Experimental Arrangement

The purpose of this investigation is: a) to test the braking characteristics of the ER coupling, i.e., to assess the torque transmission when the output shaft is braked and b) to see how temperature influences torque transmission in an ER device. The experimental arrangement is shown in Figure 3.12. The functions of the facilities used in the experiment are specified as below:

1. <u>The ER brake:</u> The structure of the ER brake has been described above. The input shaft, which is electrically live, is connected to the output shaft of the motor (3) through a "Fenner" flexible coupling (2) with a nylon spider in between.

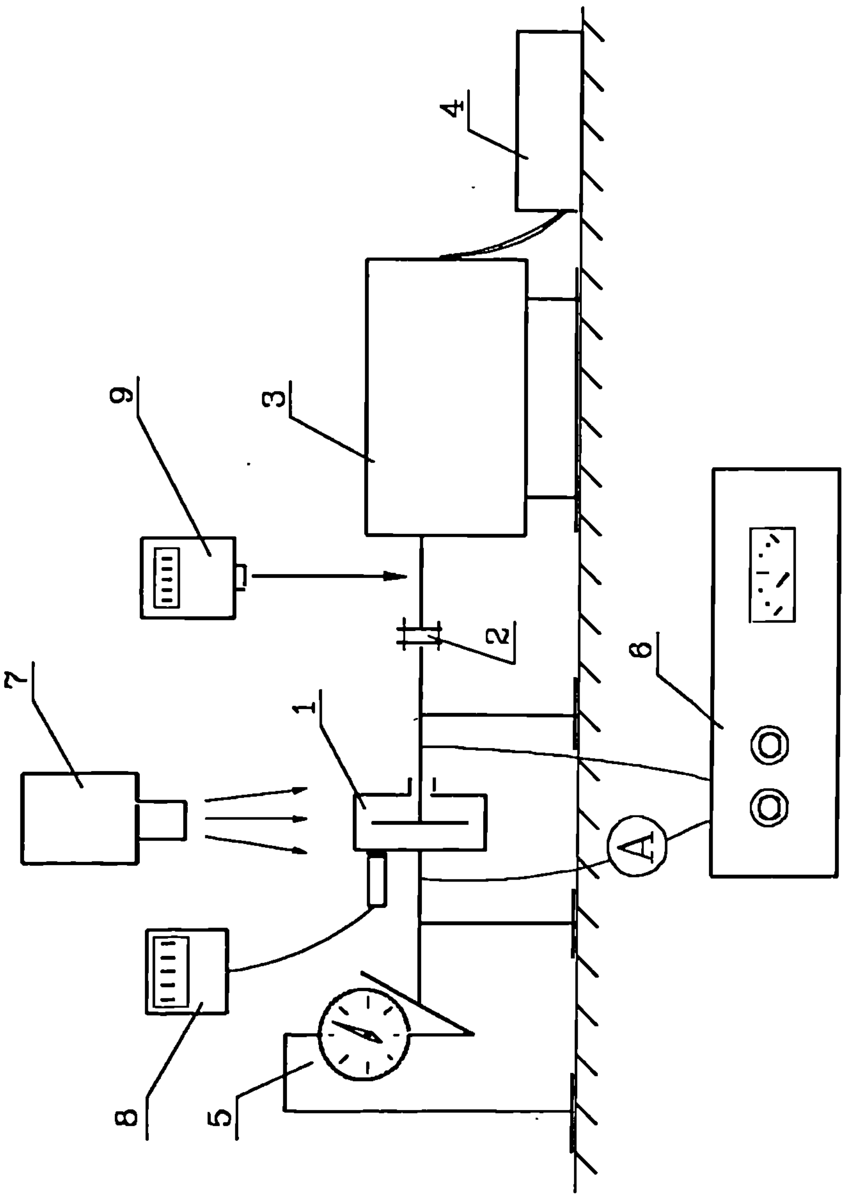

Figure 3.12: Arrangement of an ER brake experiment 1.Brake, 2.Connection coupling, 3.DC Motor, 4.Motor controller, 5.Weight, 6.High voltage generator, 7.Cooling fan, 8.Thermometer, 9.Speedometer

2. The DC motor: The brake is driven by a 0.5 hp "Neco" thyristor-controlled DC motor (3) which provides a continuously variable speed from 0 to 2,000 rpm.

3. Speed measurement: The speed of the motor shaft, i.e., the input speed of the brake is measured by a "Compact 6000" Optical Digital Tachometer (9) which provides an accuracy of $\pm$ 1 rpm. Readings are updated every 0.6 seconds and the last reading can be held manually.

4. Torque measurement: The tests are carried out with the output shaft braked by a moment arm of length of 0.25 m. A weight is then employed to measure the force exerted by the moment arm. The transmitted torque can then be indirectly calculated as the product of the force and the length of the arm. The force reading is accurate to within $\pm$ 0.05 kg.

5. Temperature control and measurement: a variable speed electric fan blower (7) is provided to cool the brake. When the fan is not working, the temperature of the ER fluid and of the outer surface of the driven part increases with running time and with load on the brake. An approximately constant temperature can be maintained by varying the speed of the cooling fan. As it was difficult to monitor the temperature of the working ER fluid, the temperature of the surface of the driven part is indicative of that of the fluid. Thus the latter temperature is used as the temperature of ER fluid in this investigation. Temperature is measured by a "Comark" thermometer (8) accurate to $\pm 1°C$. Digital reading is to the nearest $0.1°C$ and is updated every second. Temperatures are measured when the brake is working. Thus characteristics indicating the influence of temperature on torque transmission can thus be obtained.

6. High voltage generator and measurement: a "Brandenburg" (Alpha II Range) Model 2807R High Voltage DC Power Supply (6) is used as the generator. This high voltage generator provides an adjustable output voltage from 0 to 30 kV with an accuracy of ± 100 V and a maximum output current of 1.0 mA. The generator incorporates high stability and full electronic protection against short circuit and output overload, i.e., it trips when the current exceeds 1.0 mA. The integral voltmeter is calibrated and used to measure the applied voltage.

7. Current measurement: the current passing through the ER fluid is measured by a Universal "Avometer" Model VIII (10) which is connected in series with the Brandenburg high voltage generator. Thus allows currents as small as 1.0 μA to be measured.

3.4.3 Experimental Procedure

3.4.3.1 Torque Transmission at Constant Temperature

The working chamber of the ER brake is cleaned and dried before ER fluid 'A' (see appendix A) is added. The output shaft is braked via the moment arm and the input speed of the ER brake is kept constant in order to maintain a constant speed difference. Before a voltage is applied to the ER brake, the input shaft is left running at 300 rpm for a short time with the cooling fan running at medium speed. The input speed and the surface temperature are monitored. When the temperature is stable, the reading of the weight is recorded.

As the torque applied on the motor changes because of the variations in voltage applied on the device, the input speed must be adjusted by the motor controller, in order to keep the input speed constant at 300 rpm. This process is repeated until the voltage is maximum, i.e., before an electrical discharge occurs through the fluid. The speed of the cooling fan is also increased with the voltage and thus the transmitted torque is increased. The recording of the experimental data should be made as quickly as possible in order to minimise the effect of slight changes in temperature.

Again the above procedure is repeated for a constant input speed of 600 rpm.

3.4.3.2 Temperature and Current Influence to Torque Transmission

Using fluid 'A', without the cooling fan, the output shaft is braked while the input shaft speed is kept constant at 900 rpm. With the voltage set at 4 kV or 5 kV, the temperature, current and weight reading were then recorded. It is necessary to adjust the motor speed controller in order to keep the shaft input speed constant. The temperature increases with the continuous running time of the brake. Electrical breakdown occurs when the temperature is about $60°C$. When the ER brake cools down to room temperature, the above procedure is repeated at 8 kV. The current passing through the fluid is also recorded.

The above process is repeated at a different input speed of 600 rpm with fluid 'B'. However, in this case, a similar test with no voltage applied to the fluid is carried out to find out the temperature influence on the pure viscous effect.

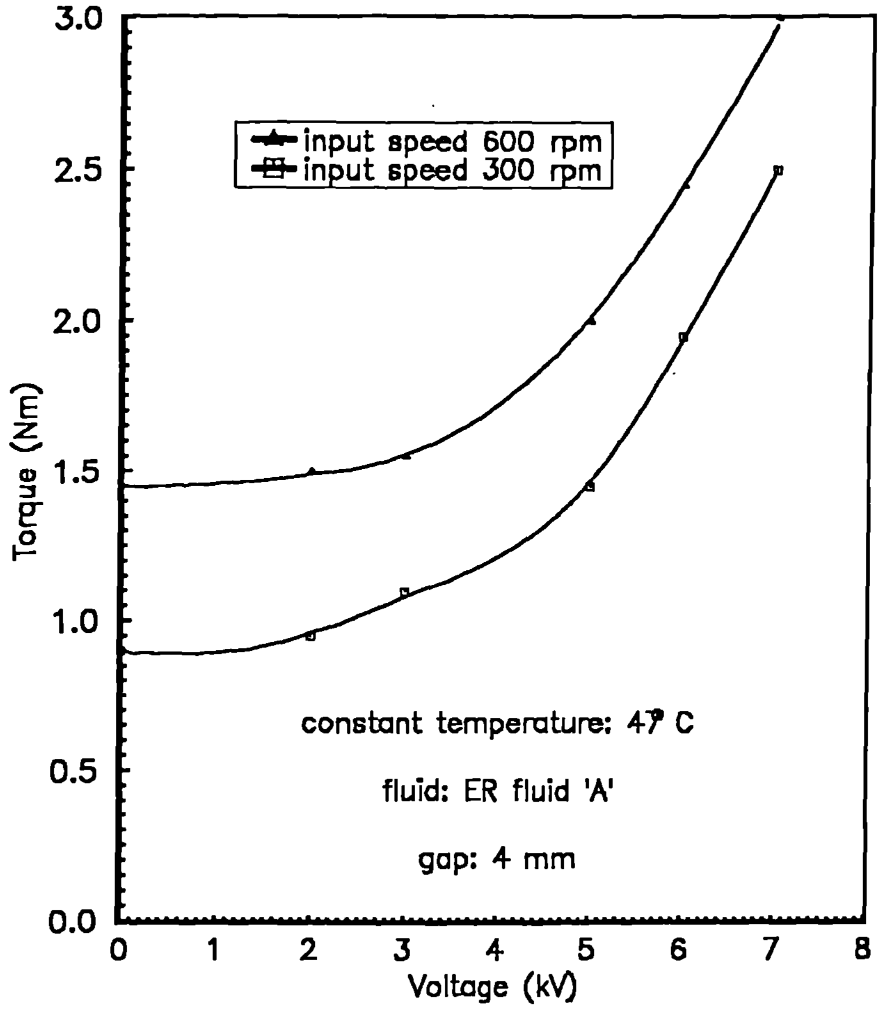

Figure 3.13: Relationship between torque and applied voltage

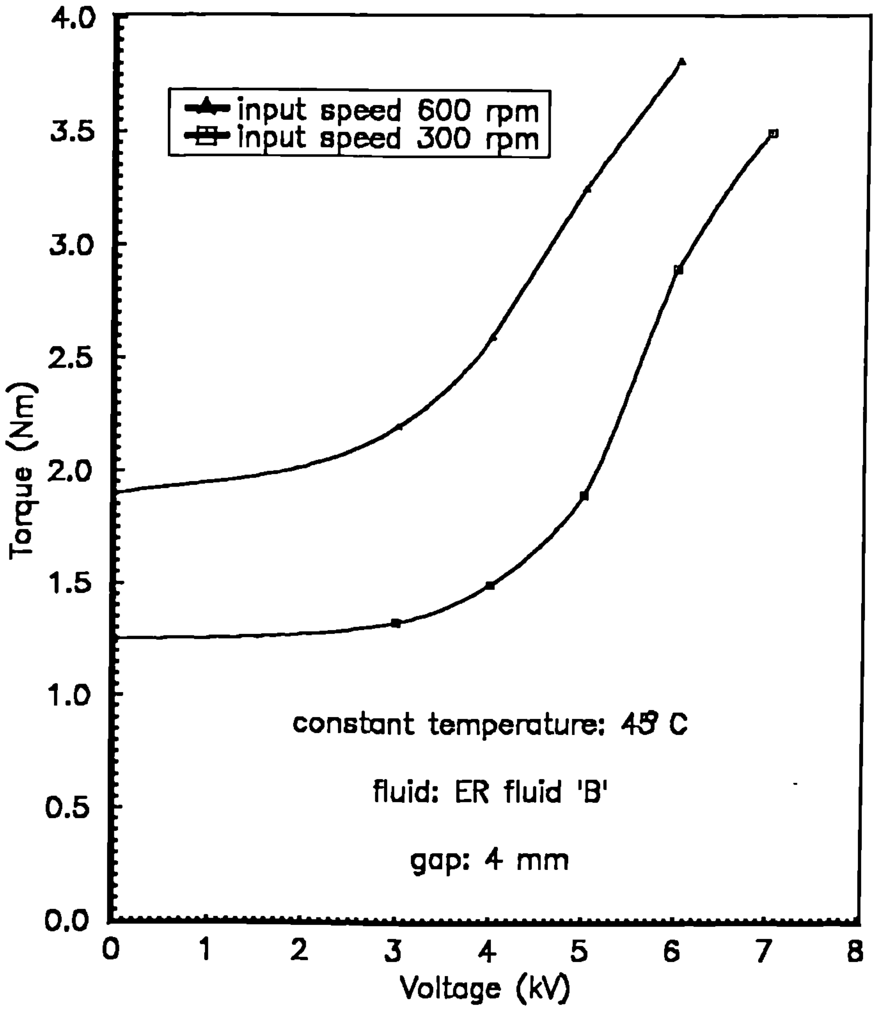

Figure 3.14: Relationship between torque and applied voltage

3.4.4 Results and Discussion

3.4.4.1 Constant Temperature Torque Transmission

Figure 3.13 shows the results with fluid 'A' and Figure 3.14 shows the results with fluid 'B'. The trend of torque changing with applied voltage is as follows:

1. The brake torque increases with the increasing voltage when the temperature and input speed are kept constant. This torque increase is very slight when voltage is low (below 2 to 3 kV), but then increases dramatically at higher voltages.

2. The brake torque increases with the speed difference between the driving and driven parts. However, the torque transmitted is not directly proportional to the speed difference as stated in equation (3.10). This is probably because of the inherent friction in the three bearings and the lip seal in the brake. The friction torque is approximately the same at different working conditions.

As fluid 'B' has a higher base viscosity than fluid 'A', the brake torque transmitted by fluid 'B' is also larger than that by fluid 'A'. It is desirable that an ER fluid transmits a large range of torque. In this sense, fluid 'B' seems to be more effective than fluid 'A'. However, the zero voltage torque transmitted by fluid 'B' is also higher than that of fluid 'A'. This is certainly not desirable. Therefore, it is difficult to say which fluid is better. The compromise depends on each particular application.

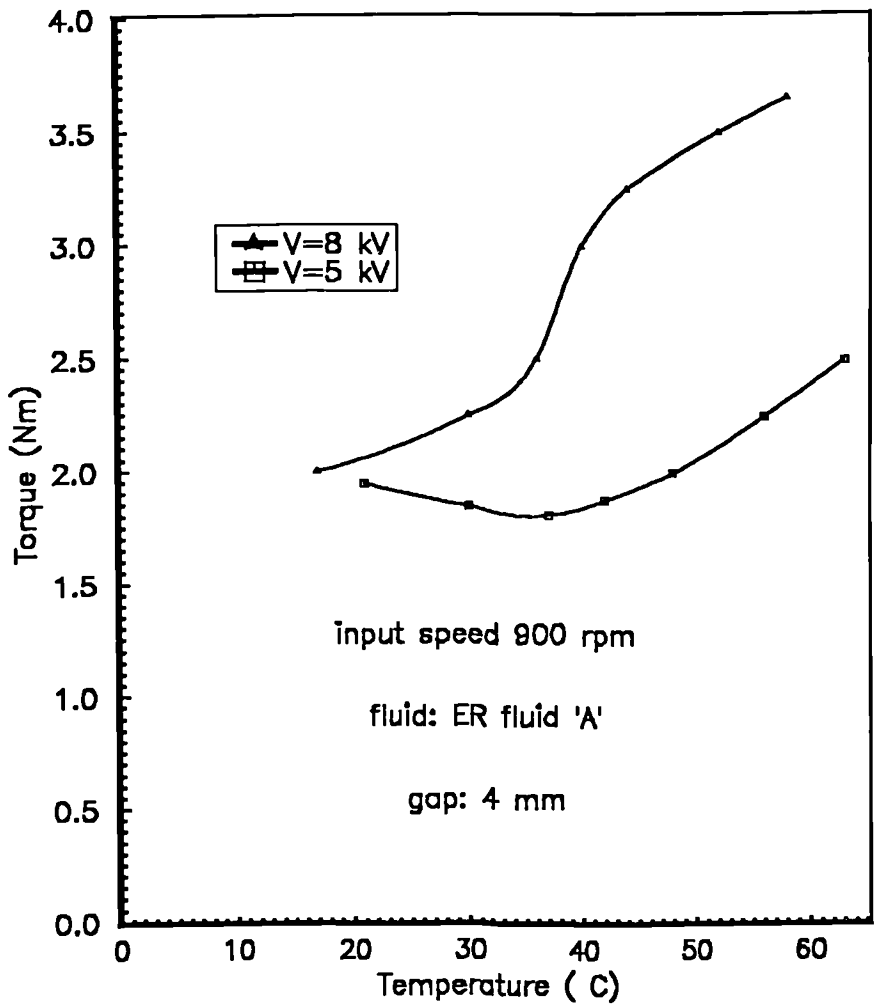

Figure 3.15: Temperature influence on torque transmission

3.4.4.2 Temperature and Current Effect on Torque Transmission

Figure 3.15 and Figure 3.16 show respectively the relationship between braking torque and temperature for fluids 'A' and 'B'. It can be seen that the

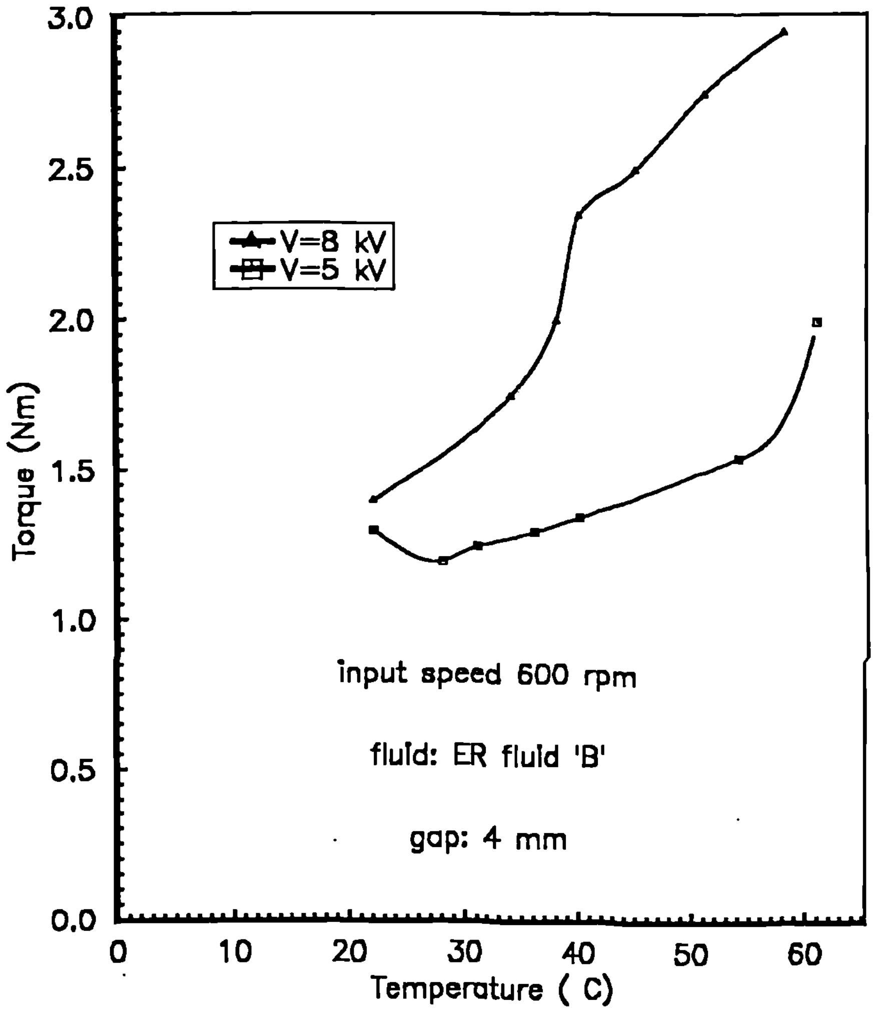

Figure 3.16: Temperature influence on torque transmission

brake torque generally increases with increasing temperature. This conflicts with the common sense that the increase of temperature usually causes a decrease of fluid viscosity thus the torque transmitted through the fluid.

It is clear that, for example at 8 kV, the torque increases by a factor of 2 when the temperature increases from 23°C to 60°C. At 4 or 5 kV, the increases by a factor of 1.5.

The torque transmitted across the ER brake is made up of two components, pure viscous torque T_v and pure electrorheological torque T_e. It is well known that an increase of temperature usually causes a decrease of fluid viscosity and thus a decrease of torque transmitted by the fluid. Figure 3.17 shows the relationships between the torques (pure viscous, pure electrorheological and combined) and temperature. Note that the pure viscous torque always decreases with temperature and the pure electrorheological torque increases with temperature.

As a consequence, when the voltage is high, the pure ER effect is very strong and the decrease in the pure viscous torque cannot make the general torque decrease. When the voltage is low, the reduction in the pure viscous torque is larger than the increase in pure ER torque (under around 30°C). This is reversed when the temperature is higher. This phenomenon could make ER fluids more promising in practical applications.

The reasons why the pure electrorheological torque increases with temperature are not very clear. However, it is appropriate to attribute this change to the change in the current passing through the ER fluid, because the current is the only parameter changed except the transmitted torque due to the change of temperature. Figure 3.18 shows the relationship between current and temperature. It is shown that the current increases with increasing temperature just as the pure electrorheological torque does.

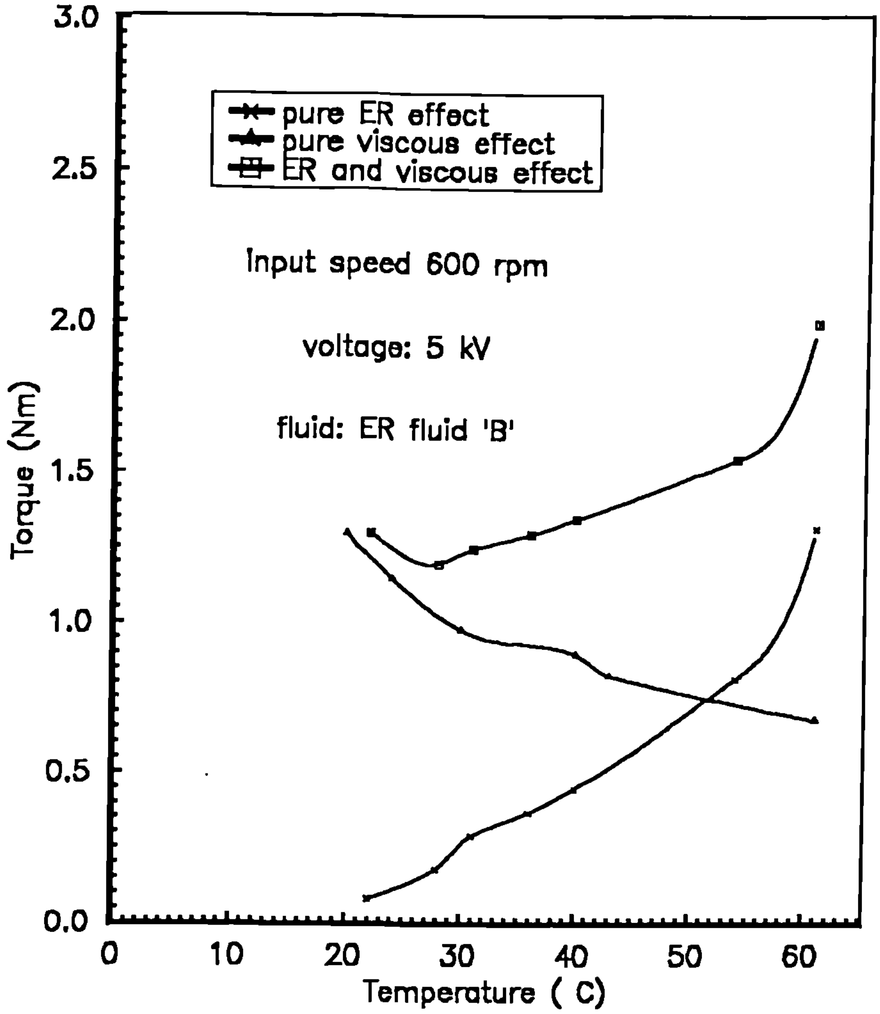

Figure 3.17: Temperature influence on pure ER and viscous effects

3.4.6 Concluding Remarks

From the above results and analysis, it can be concluded that the ER brake demonstrates that braking torque increases with applied voltage. The higher

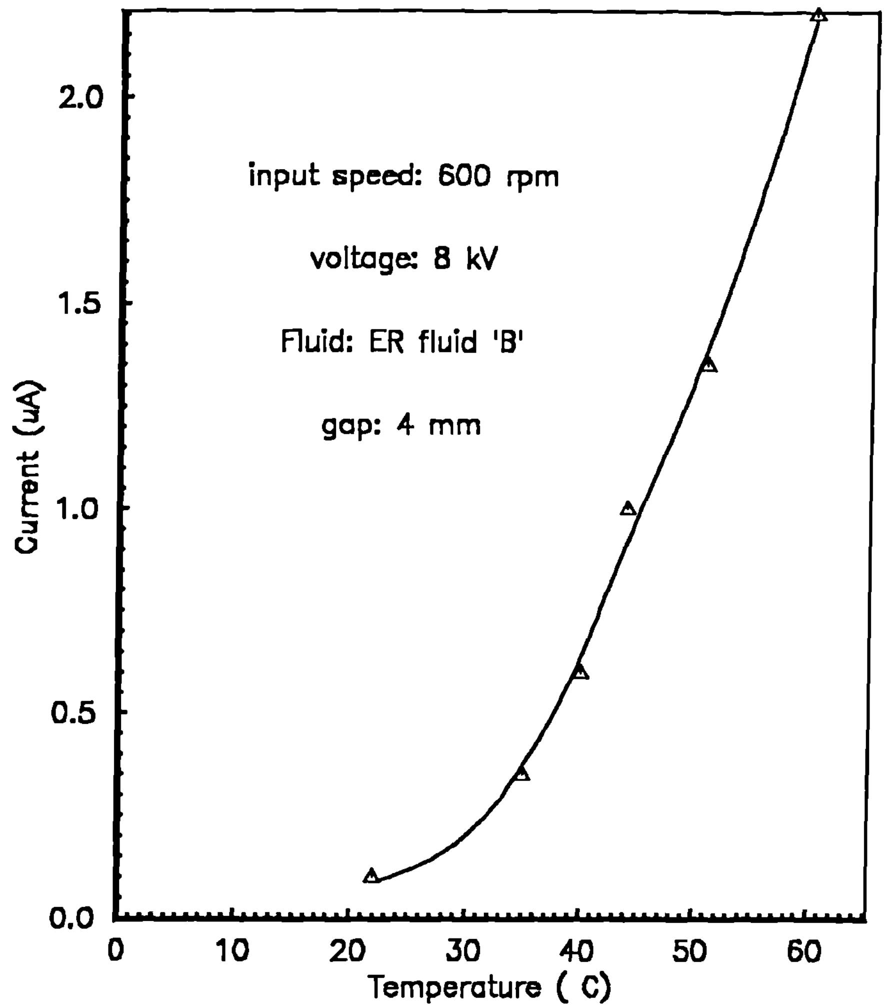

Figure 3.18: Current increases with temperature

the voltage an ER fluid can sustain, the larger the torque that can be transmitted.

Regarding the influence of temperature on the ER effect, it seems that there exists a critical temperature and a critical voltage, below which, the pure viscous effect is stronger than the pure ER effect. When the temperature increases below the critical value, the pure viscous effect weakens, and the torque transmitted decreases. However when the temperature exceeds the critical value, the ER effect becomes very strong. Thus as the temperature continues to increase, the ER effect becomes stronger and stronger until an electric breakdown point is reached.

Therefore it can be inferred that when the temperature increases, the electrical resistance of the ER fluid will decrease. This causes the current flowing through the fluid to increase. The increase in current strengthens the ER effect. The voltage and current applied to the ER fluid are factors which both benefit the ER effect. However, there is a limiting value for the current at which point the ER fluid breaks down or the high voltage generator will trip. The higher the power an ER fluid consumes, the better the ER effect. Hence in terms of mechanical performance, the best ER fluids are those which can endure a high voltage and a large current.

3.5 An Experiment Involving an ER Cooling Fan Drive

The purpose of this section is to examine the feasibility of an ER fan drive for use with a motor vehicle cooling system. Therefore, it was decided that the ER fan drive should be compatible with the existing viscous fan drive used in the Jaguar XJ12 range of cars. The performance specifications stipulate that the fan drive must a) maintain a 1:1 drive ratio in the range from 800 to 2,250 rpm; b) give a fan speed saturation at 2,250 rpm as the engine speed is increased up to 4,500 rpm; c) is capable of reducing the fan speed to a minimum value within the range of 400 to 1,000 rpm depending on engine speed. These requirements are shown graphically as the area circled by the heavy line in Figure 3.21.

3.5.1 Structure of the ER Fan Drive

The external configuration of the fan drive is dictated by the design of the existing viscous fan drive, as shown in Figure 3.19. Referring to Figure 3.19, the driving plate (6), which forms the live electrode, is bolted onto the PTFE separator (1) which in turn is secured on the metal input shaft (2) by a long bolt (11). The drive casing consists of two parts (7) and (13). The left-hand part, onto which the fan blades are bolted (5), is mounted on the input shaft through a rolling element bearing (3). The right-hand part is supported at the edge of the driving plate (6) by a live bearing (10) which is prevented from touching the casing by a PTFE spacer. Two lip seals (4) and (9) are used to prevent the ER fluid reaching the two bearings. The live parts in the right-hand side of the drive are covered by PTFE with the exception of a live tip which is left bare for the connection of the high voltage through a slip ring arrangement.

The gap between electrodes is 7 mm, the outer diameter of the live plate is 125 mm and the inner diameter is 75 mm. These dimensions are based on the requirements stated above, and on the assumption of a 10 kPa ER fluid being available.

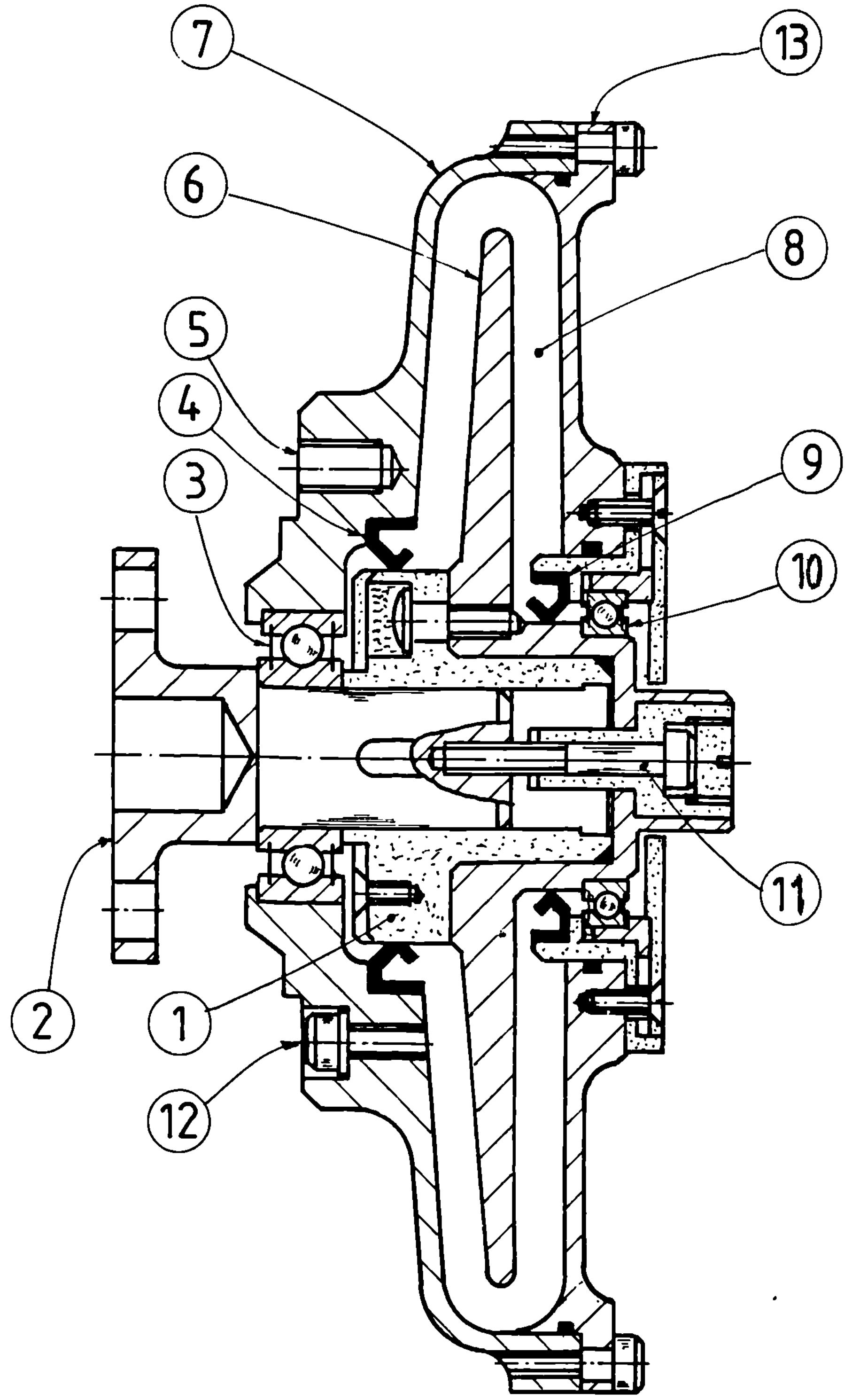

Figure 3.19: An ER fan drive 1.Insulating separator, 2.Input shaft 3,10.Bearing, 4,9.Lip seal, 5.Fan blade connection, 6.Live plate, 7,13.Casing, 8.Fluid chamber, 11.Secure bolt, 12.Refilling hole

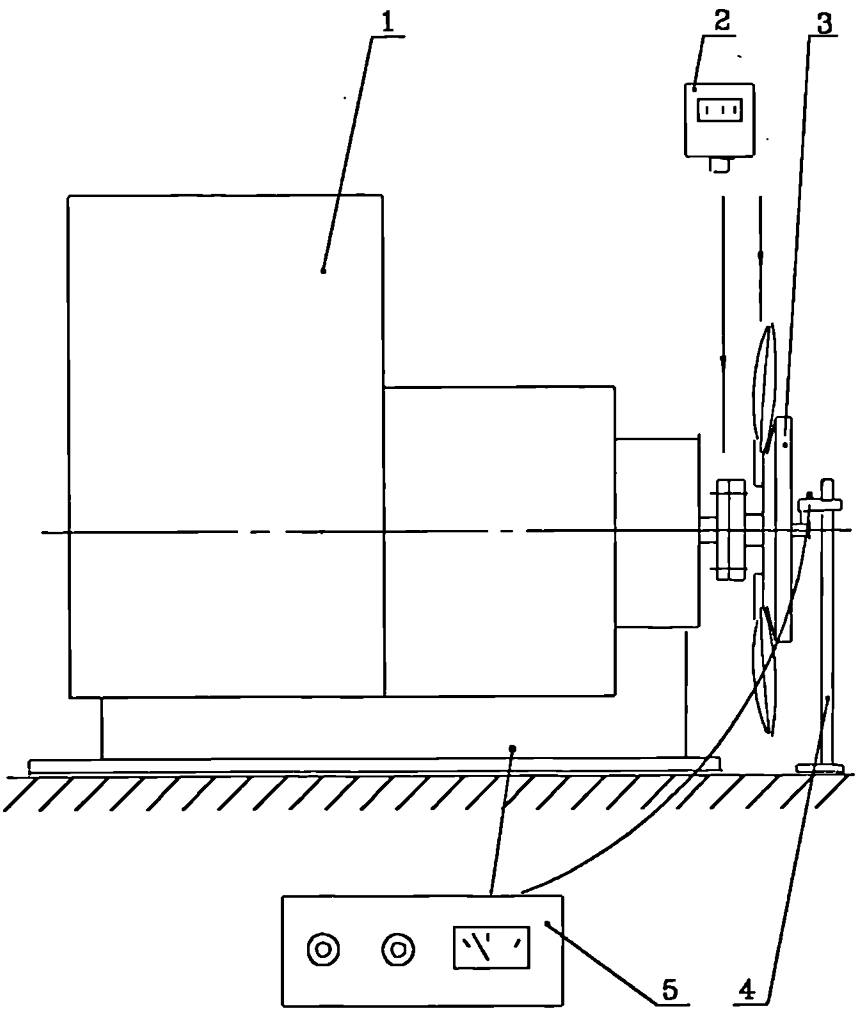

Figure 3.20: Arrangement of an ER fan drive experiment

1.Engine, 2.Speedometer, 3.Fan drive body, 4.Electric brush holder, 5.High voltage generator

3.5.2 Experimental Arrangement

For testing purposes, the fan drive unit was fitted to a four-cylinder 1500 cc "Austin" internal combustion engine test station, capable of providing a maximum speed of 4,500 rpm, as shown in Figure 3.20. For various mechanical reasons it was not possible to mount the drive unit at the front-end of the engine, and so in the present arrangement the fan was driven in a sense opposite to that for which the fan was designed. The unit was not provided with forced cooling.

1. Connection of the ER fan drive: the fan drive unit (3) is bolted to the engine main shaft. The slip ring holder (4) is mounted onto the test station. This arrangement allows the high voltage to be applied to the fan drive easily.

2. Engine: as described above, the engine is a 1,500 cc four-cylinder Austin which is revised for the fan test.

3. Input speed and output speed measurements: the input speed of the fan drive is derived from the output speed of the engine shaft. This speed is controlled by the engine's throttle. The speed of the fan shaft and fan blade are monitored by the same electro-optical tachometer (2) used in the last experiment.

4. High voltage generator: The Brandenburg high voltage supply (5) is also used in this case.

3.5.3 Experimental Procedure

3.5.3.1 Variable Speed Test with Different ER Fluids

Before assembly, the internal components of the fan drive unit are cleaned with acetone and then dried, especially the driving plate and the inner surface of the casing. The drive is filled with ER fluid 'A' through the two holes on the left-hand side of the casing. Care was taken to ensure no air bubbles are present in the working chamber. The engine shaft speed is adjusted so that the input speed of the fan drive is 800 rpm. The input speed and the output speed are then recorded with no voltage applied to the fan drive. The voltage is then increased to the maximum value before electric breakdown and the speed of the fan blade recorded. Checks were made to ensure that the input speed remained constant at 800 rpm.

The above procedures were repeated at input speeds from 1,200 to 4,000 rpm in steps of 400 rpm.

The above procedures were repeated using ER fluid 'C'.

The series of fan speed experiments at maximum electric voltage produced an 'upper limit' characteristic whilst those with no voltage produced a 'lower limit' characteristic. These limits define the range over which a continuously variable control of the fan speed is available.

3.5.3.2 Friction Tests

In the prototype device, it was found that significant friction torques were introduced by the bearings and seals. Consequently, tests were performed, in the absence of ER fluid, to quantify these frictional effects.

Initially, it is ensured that there is no ER fluid remaining in the working chamber. The output speed was recorded for input speeds from 800 to 4,000 rpm in steps of 400 rpm. Under these circumstances, the output shaft is driven exclusively by the friction present in the bearings and seals.

3.5.4 Experimental Results and Discussion

Figure 3.21 shows the full set of experimental results both with and without ER fluids in the working chamber. Although the ER fan drive demonstrated a continuously variable output speed simply by the change of voltage applied to it, the variable speed range does not meet the requirements stated in the original specification.

The upper limit of fluid 'A' shows that the fan drive is unable to maintain the 1:1 ratio required in the range 1,000 to 2,250 rpm (broken curve (a)). With the lower limit the consequent reduction in fan speed is almost insignificant (broken curve (b)).

With fluid 'B', the upper limit shows that the fan drive can hold the 1:1 ratio up to a speed of about 1,500 rpm but thereafter the fan speed does not increase as rapidly as the engine speed. As engine speed approaches to 4,000 rpm, the fan speed is only 2,100 rpm (curve (a)).

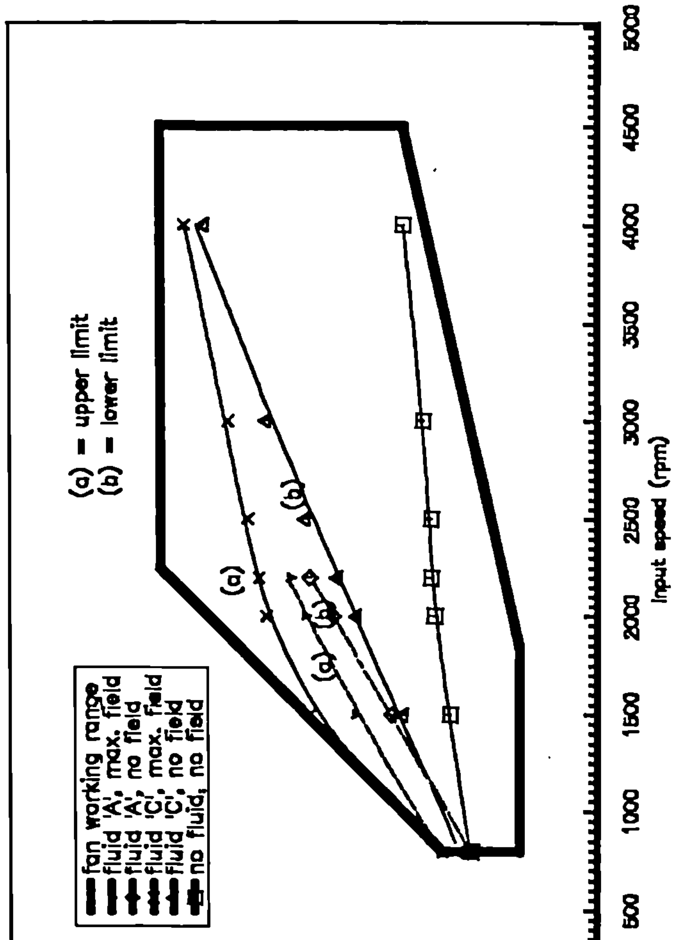

Figure 3.21: Characteristics of the ER fan drive

The upper limit of fluid 'B' represents a significant improvement over that achieved with fluid 'A'. However, its lower limit is only slightly down on that achieved with fluid 'A'.

Results in the absence of ER fluid show the fan speed gradually increases from 800 rpm to approximately 1,000 rpm as the engine speed is increased from 800 rpm to 4,000 rpm. This speed increase results solely from the frictional torques in the bearings and seals.

The results indicate that the ER fan drive does not meet the original specification. It is clear that better ER fluids and reduced friction in bearings and seals are necessary for this device. Even ignoring the fan's original design requirement, the variable speed range of the fan drive is not satisfactory.

However, it should be noted that the lower limiting characteristics can be approached with the present fluid by enlarging the gap between the electrodes. To reduce the bearing and seal friction would, of course, improve the lower limiting characteristic, but this would be achieved at the expense of the upper limiting characteristic. A better ER fluid is essential for the ER fan drive to be a practical device.

Modifications can also be made to change the working chamber of the fan drive, i.e., to obtain a variable fluid volume chamber as that used in many viscous fan drives. This will make the configuration of an ER fan drive more complicated but should enable the design specification eventually to be met.

3.5.5 Concluding Remarks

The above results demonstrate that the ER fan drive can achieve a continuously variable output speed by changing the voltage applied to the ER fluids. However, the continuously variable range is limited because:

1. The electrically induced shear stress of the ER fluids is not large enough;

2. The inherent viscosity of the ER fluid is too large and the frictional torques introduced by the bearings and seals is too great.

It has also been demonstrated that no imposed cooling is required for the fan drive to maintain a steady working temperature.

3.6 Experiments with an ER Drive Shaft

The ER drive shaft was intended eventually for automotive applications where speed/torque control of each driven wheel is required. The application space constraints include a maximum outside diameter 102 mm and maximum length 457 mm. For practical applications, the device should be capable of transmitting a uniform torque 42 Nm over the full speed range from 0 to 5,000 rpm.

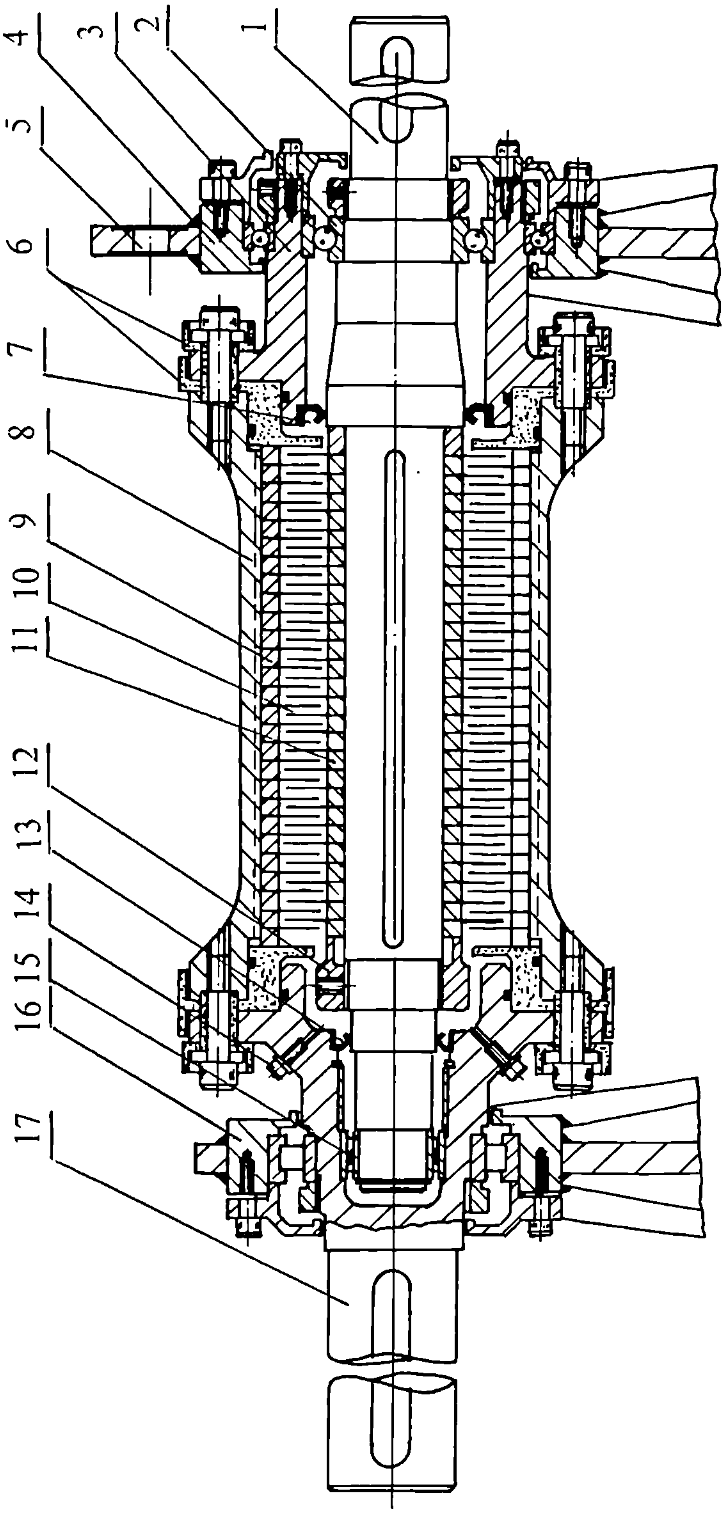

Figure 3.22: An ER drive shaft. 1.Input shaft, 2.Bearing, 3.Right-hand cap, 4,16.Stand, 5.Electric brush holder, 6.Insulator, 7,13.Lip seal, 8.Live drum, 9.Live plate, 10.Fluid chamber, 11.Earthed plate, 12.Sccure screw, 14.syringe, 15.Needle bearing, 17.Output shaft

3.6.1 Structure of the Drive Shaft

The constraint on the maximum diameter was strictly adhered to. However the overall length between bearing centres was limited to 296 mm for convenience of construction and experiment.

Owing to constraints on size and the torque to be transmitted by the drive shaft, it was decided that a multiplate configuration would be better for the arrangement of electrodes. By using equation (3.6), assuming the maximum shear stress of ER fluid to be 7 kPa which is a medium value, as ER fluids of up to 15 kPa are reported to be available [113,114], and choosing the gap between the electrodes as 2 mm, the effective outer diameter of plates to be 100 mm, the effective inner diameter of plates to be 45 mm, it was found that 27 pairs of plates resulted to be accommodated in the drive shaft. An assembly drawing of the drive shaft is shown in Figure 3.22.

One end of the input shaft (1), which acts as the earthed electrode, is supported on the right end cap (3) by a rolling bearing (2) while the other end is supported on the output shaft (left end cap (17)) by a needle bearing (15). The right end cap (3) is bolted on to the live plate drum (8) and the arrangement is insulated by incorporating several PTFE separators (6). Before the left end cap is assembled, live plates (9) and earthed plates (11) are placed alternately on the drum (8) and input shaft (1) through the keyways from the left end of the drive shaft. The position of earthed plates is secured by a screw (12). The connection between the left end cap (17) and the drum (8) has the same arrangement as that of the right-hand part. The position of the live plates is secured after the left cap is secured on to the drum. Two lip seals (7,13) are used to prevent the ER fluid leaking from the working chamber

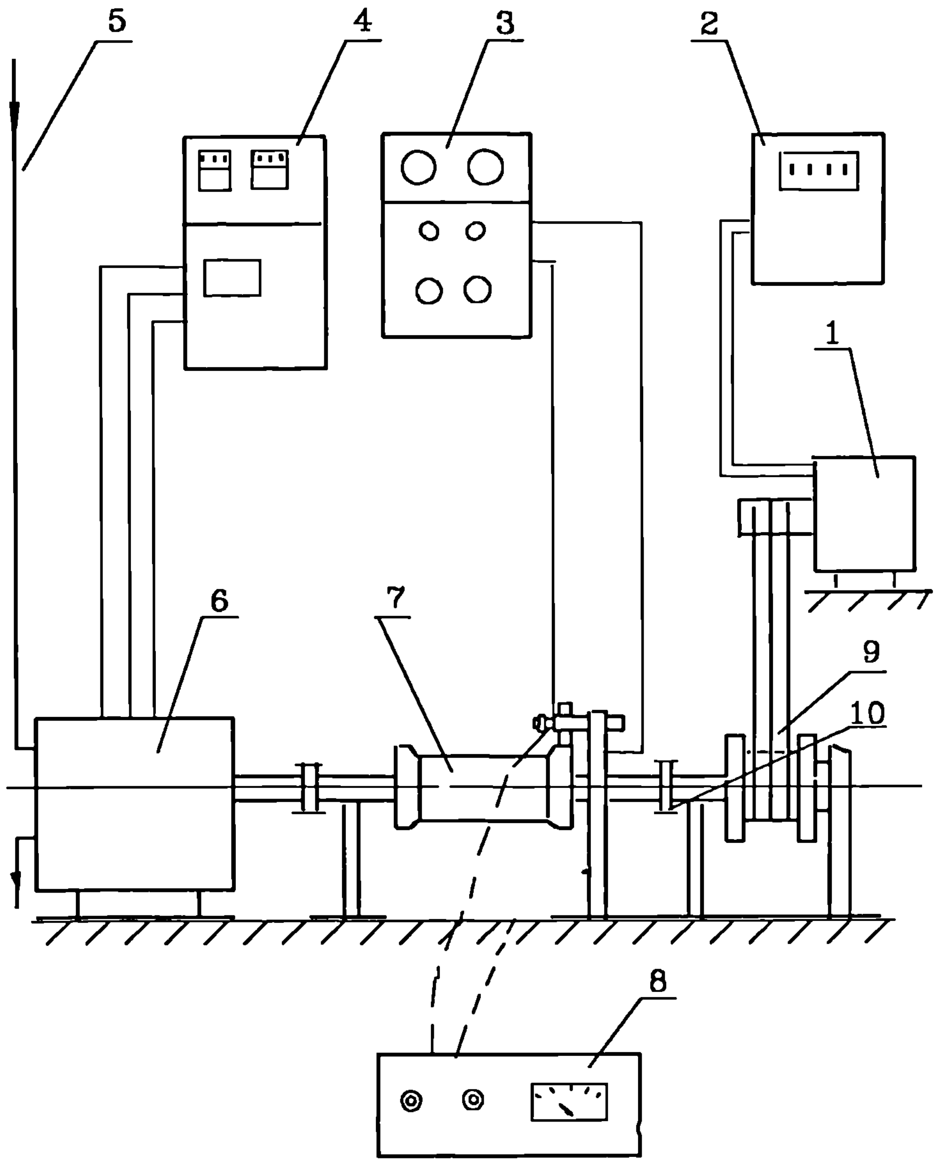

Figure 3.23: Arrangement of the ER drive shaft experiment 1.DC Motor, 2.Motor Controller, 3.High Voltage Generator, 4.Dynamometer Controller, 5.Cooling Water Supply, 6.Dynamometer, 7.Drive Shaft, 8.High Voltage Generator, 9.Belt drive, 10.Flexible Coupling

(10) and reaching the bearings. The whole device is supported on two stands (4) and (16) at each end. A slip ring holder is secured on (5) for the high

voltages to be applied on the right-hand end edge of drum (8). There are two holes (14) on the left end cap for introducing the ER fluid.

3.6.2 Experimental Arrangement

The purpose of the experiment is to investigate the feasibility of the drive shaft as a continuously variable torque and power transmission device. Figure 3.23 shows the arrangement of facilities used in the experiment.

1. Mechanical connections to the drive shaft. Considering the requirement of alignment, two flexible couplings (10) are used to connect the input and output shafts to the motor and the dynamometer (6). This ensures that the system runs smoothly.

2. Electric motor and input speed measurement. A 22kW "Stromberg" DC motor (1) is used to drive the transmission. Due to its maximum output speed, which is not large enough for the input speed requirement of the drive shaft, a V-belt transmission (9) is used to increase the output speed of the motor by a factor of two. The motor speed is regulated by a "Fenner Speedranger" 4070 electronic controller (2), and the actual input speed of the drive shaft is shown in digital form on the control panel.

3. Load application, torque, and output speed measurement. The output shaft of the drive shaft is connected to a "Vibro-meter" 2WB 15 eddy current and magnetic powder dynamometer (6), which absorbs a rated torque 280 Nm at maximum speeds of up to 10,000 rpm. The dynamometer is cooled by circulating flowing water (5). The load applied to the drive shaft is varied by regulating the excitation current. Output

speed and transmitted torque of the drive shaft are shown in digital form on the dynamometer control panel (4). The dynamometer is calibrated before it is connected to the drive shaft.

4. High voltage supply: Instead of using the "Brandenburg" high voltage generator described in section 3.3, a higher power voltage generator was used, i.e., the "Trek" model 664 high voltage amplifier/supply system which consists of a model 662 amplifier and a model 663A high voltage power supply. The system can be used as a high voltage amplifier applied to an external signal (AC or DC), or as a reference supply and amplifier combined. In the former mode its gain is fixed at 1 kV/V with an output voltage of from 0 to ± 10 kV. In the latter mode the output voltage varies from 0 to ± 11.0 kV. In both modes the maximum output current is 20 mA and the accuracy of output voltage is ± 10 V.

A 50 Hz sinusoidal AC voltage generator was also used. This generates a fixed 50 Hz output voltage of up to 5 kV.

3.6.3 Experimental Procedure

3.6.3.1 Initial Assembly of Drive Shaft

The 27 pairs of plates were cleaned using acetone and thoroughly dried before assembly. The appropriate ER fluid was injected into the working chamber of the coupling during the plate-by-plate assembly, so as to ensure that no hydraulic jacking of the plates occurred which could produce non-uniform stacking.

After assembly of the plates and positioning of the right-hand end cap, the remaining space above the last plate was then filled by the simultaneous application of two fluid-filled syringes in the access holes, to ensure that the drive shaft was completely filled with fluid, thereby reducing the possibility of incipient electrical breakdown in an air cavity. The drive shaft was then mounted onto the test station.

3.6.3.2 Constant Voltage Test

Fluid 'A' was used for tests with the "Brandenburg" high voltage generator and also with the 50 Hz AC generator. For a fixed input shaft speed of 500 rpm and fixed DC voltages in the range of from 0 to 5 kV, the output speed was monitored for gradually increasing applied loads, obtained by increasing the excitation current. These tests were repeated for the input speeds in the initial range from 1,000 to 1,500 rpm.

The DC voltage source was replaced with the 50 Hz AC voltage and the above tests were repeated

3.6.3.3 Constant Torque Test

With a fixed input speed of 500 rpm, the output speed is monitored for gradually increasing applied DC voltages while the transmitted torque is kept constant at 0.2 Nm by varying the excitation current applied to the dynamometer. These tests are repeated for another constant torque of 0.8 Nm.

3.6.3.4 Constant Speed Ratio Test

With a fixed input speed of 500 rpm, the output torque is monitored as the voltage is increased from zero to a maximum value where the electric breakdown occurs, and the output speed is kept constant by varying the load applied to the drive shaft.

Some of the above tests were repeated using the "Trek" high voltage amplifier and supply.

3.6.4 Results and Discussion

It was observed that before the drive shaft was running, the maximum voltage that could be applied to the device without electrical breakdown was between 5.5 and 6.0 kV, which implies a maximum field strength of 2.75 to 3.0 kV/mm. This appeared to concur with previous results.

However, when the coupling had been running for a few minutes the maximum value fell within the range from 3.5 to 5.0 kV. This reduction might be due to a centrifugal effect on the suspended contaminant particles and the consequential local increase in electrical conductivity of the fluid.in the outer regions of the coupling, or due to the increased number of breakdown.

Furthermore, when the coupling was running continuously, the maximum voltage further reduced to below 4 kV, possibly due to the increase of the fluid temperature and thus the current passing through it.

The results of constant voltage tests carried out with fluid 'A' are shown in Figures 3.24, 3.25 and 3.26 in which output shaft speed is plotted against braking torque for applied voltages in the range from 0 to 4.5 kV and for input speeds kept constant at 500, 1,000 and 1,500 rpm respectively. It can be seen that the torque and the output speed increase with applied voltage, due to the increase in apparent viscosity of the fluid. For all three cases, the coupling is capable of operating in a 1:1 speed ratio when the voltage is maximum and torque is low. The variable speed range between zero voltage and maximum voltage is reasonably large, from 350 to 700 rpm, especially at the lower input speeds. Results obtained with fluid 'C', as shown in Figures 3.27 and 3.28, show similar trends. However, the transmitted torque with fluid 'C'is much larger than that with fluid 'A'.

Figures 3.29 and 3.30 show the results for the relationship between output speed and applied voltage when transmitted torque and input speed are kept constant. These results demonstrate that output speed increases with the applied voltage and decreases with applied load on the shaft. This kind of change is not so obvious at lower voltage than at voltages higher than 3 kV. Therefore it is very important to maintain the voltage as high as possible.

With fluid 'C', much better constant torque results were achieved, as shown in Figure 3.31. When the input speed is constant at 650 rpm and the constant torque is 0.2 Nm, the output speed increases from 150 rpm to 580 rpm as the voltage increase from 0 to 3.0 kV (breakdown occurs over 3.0 kV); when the torque is 0.8 Nm, the output speed increases from 30 rpm to 330 rpm.

Figure 3.32 shows a promising relationship between transmitted torque and applied voltage when both the input and output speeds are kept constant at

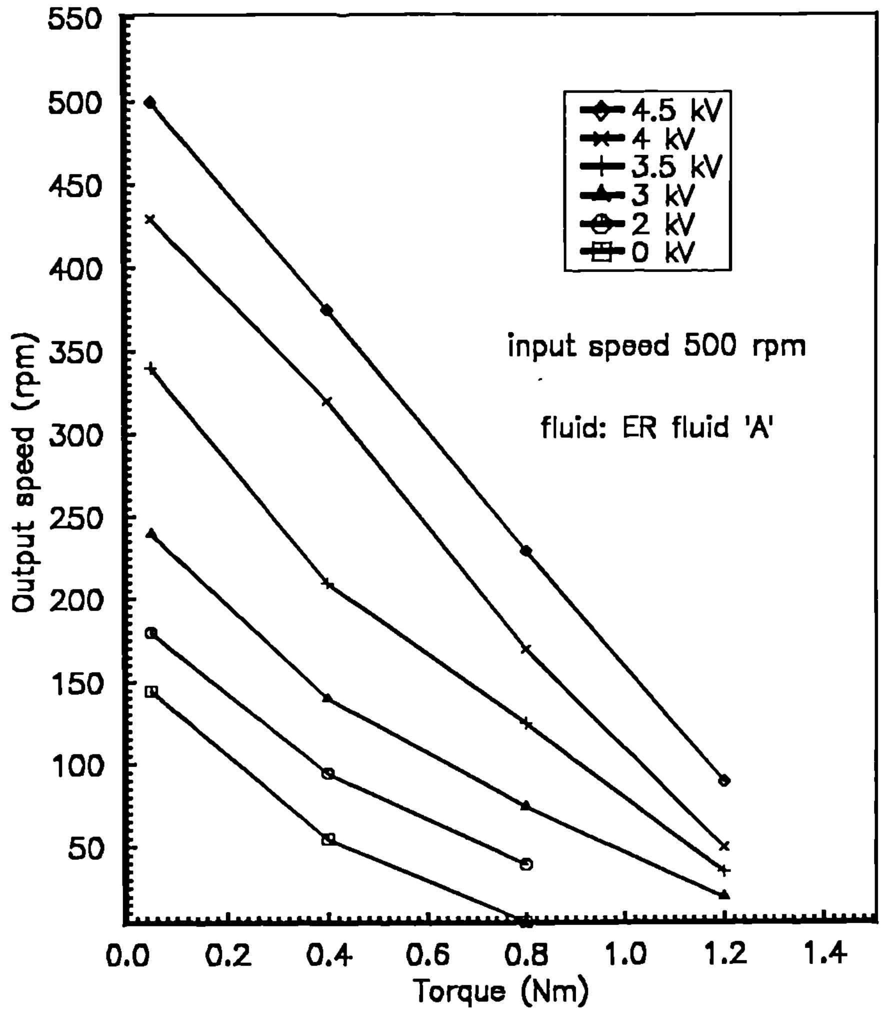

Figure 3.24: Relationship between output speed and torque at constant voltage

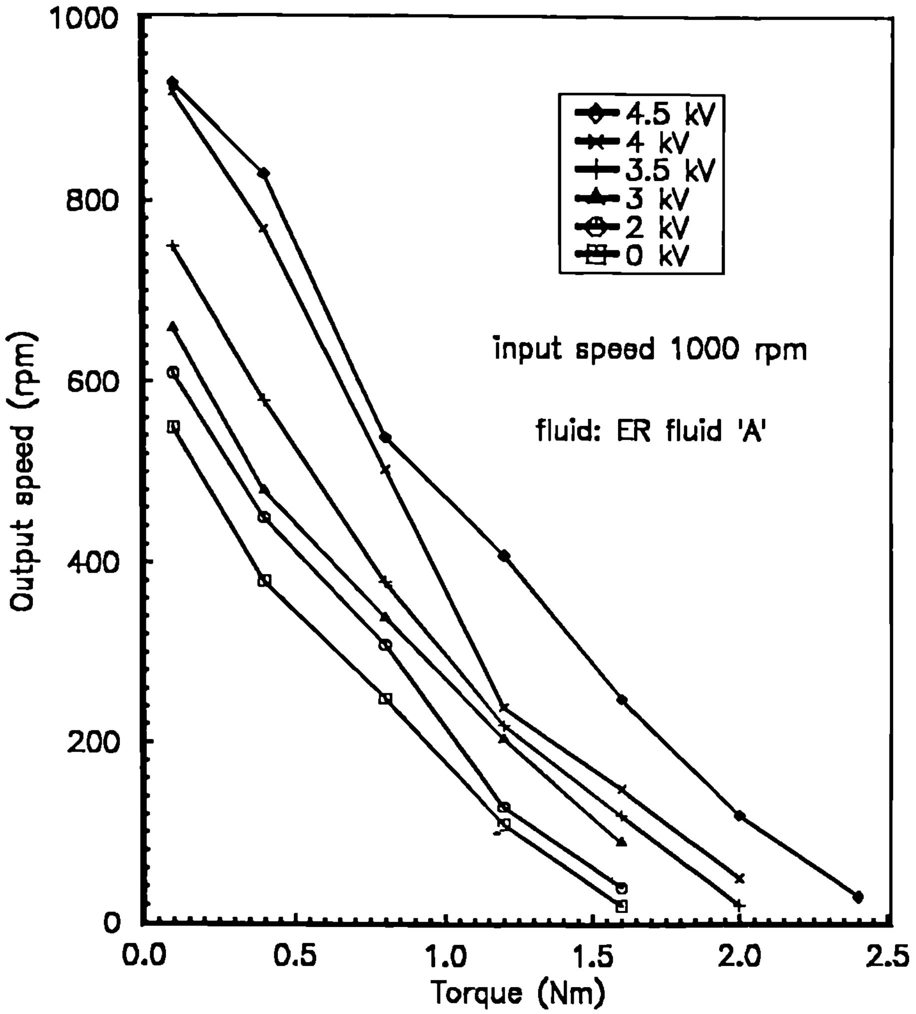

Figure 3.25: Relationship between output speed and torque at constant voltage

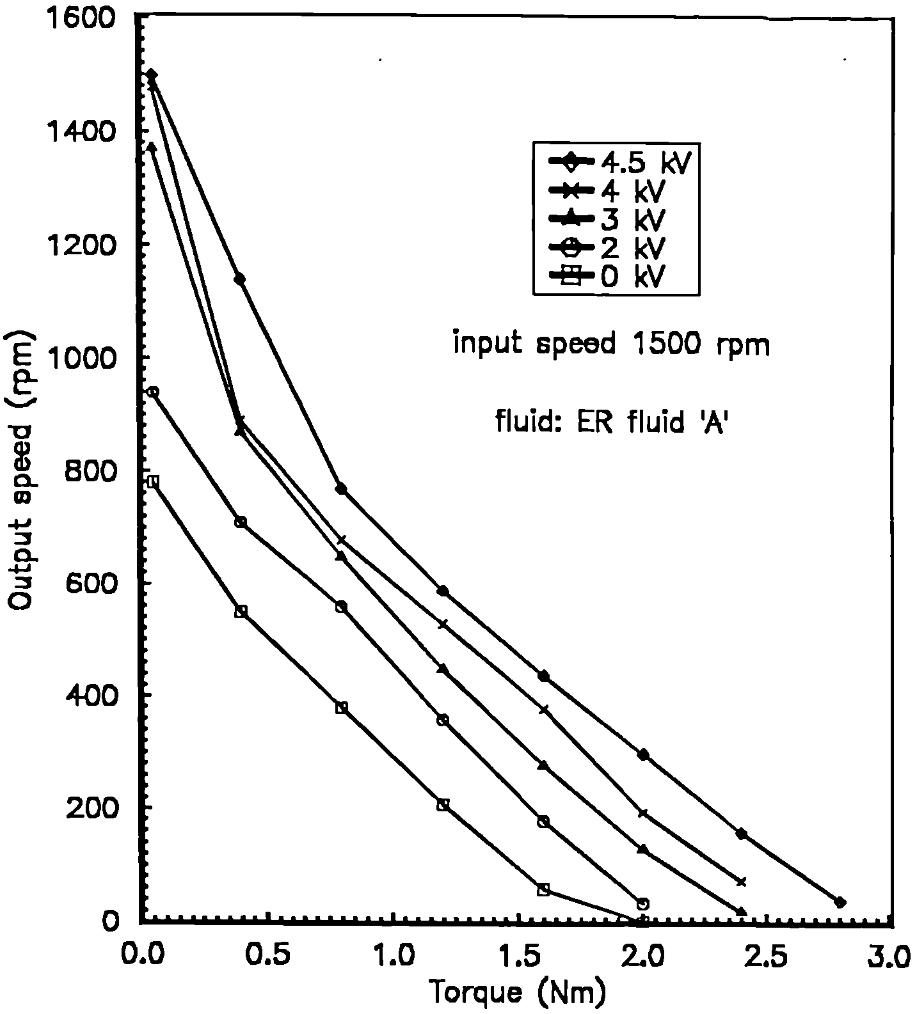

Figure 3.26: Relationship between output speed and torque at constant voltage

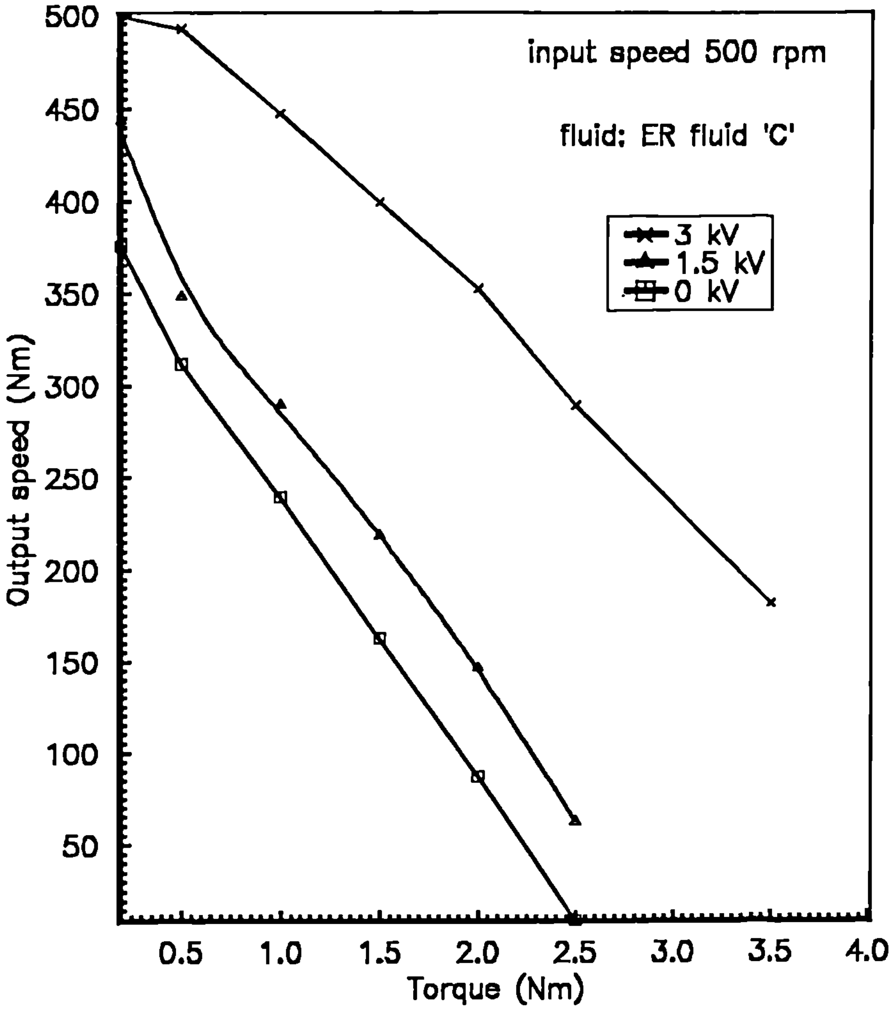

Figure 3.27: Relationship between output speed and torque at constant voltage

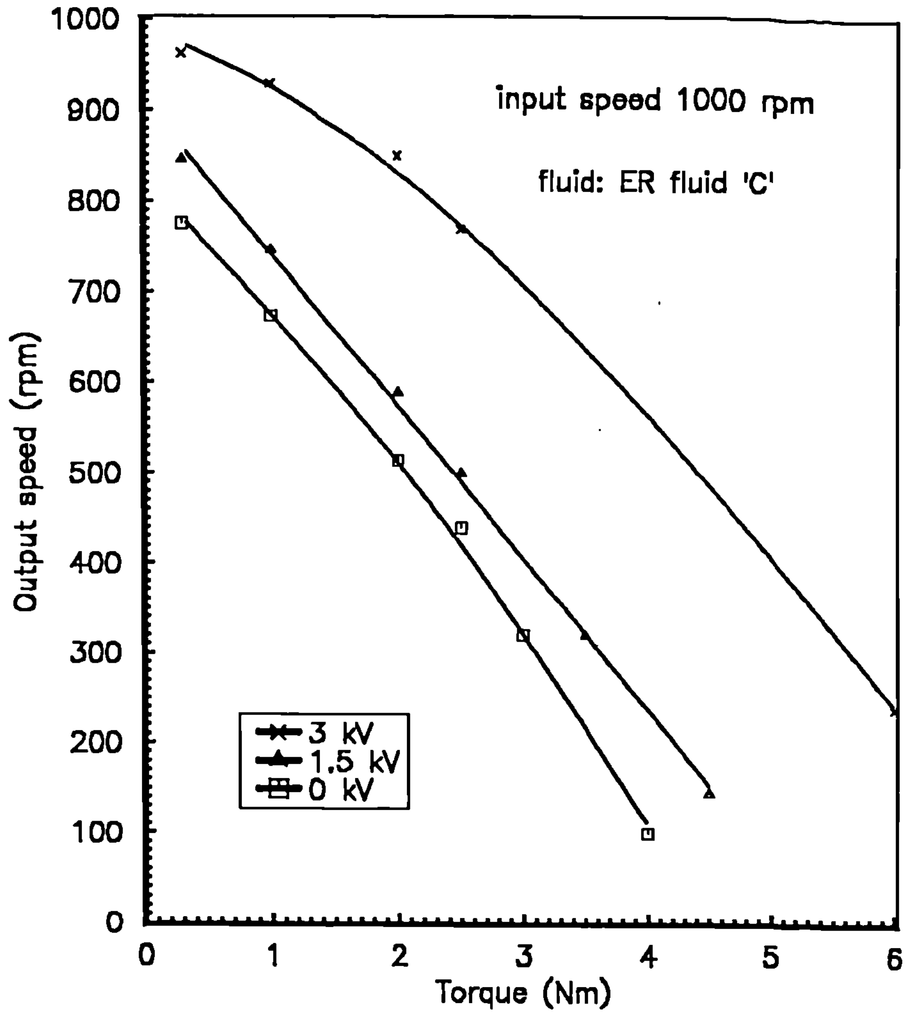

Figure 3.28: Relationship between output speed and torque at constant voltage

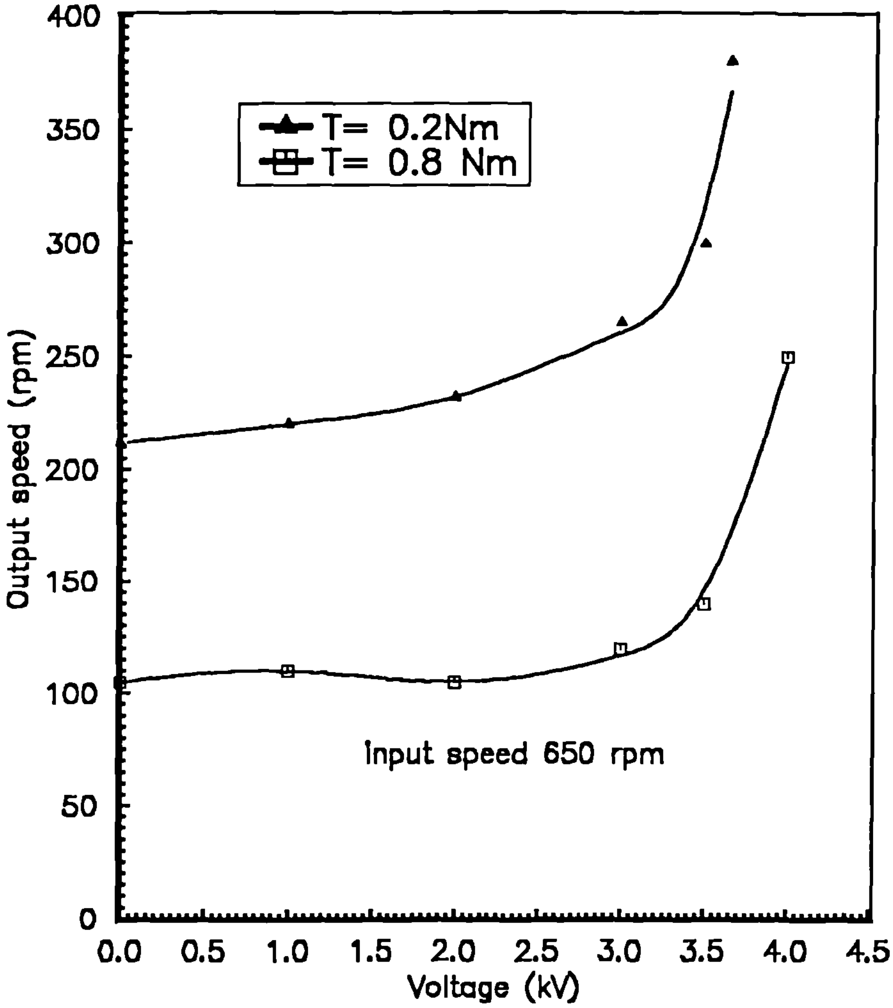

Figure 3.29: Constant torque characteristics of the ER coupling

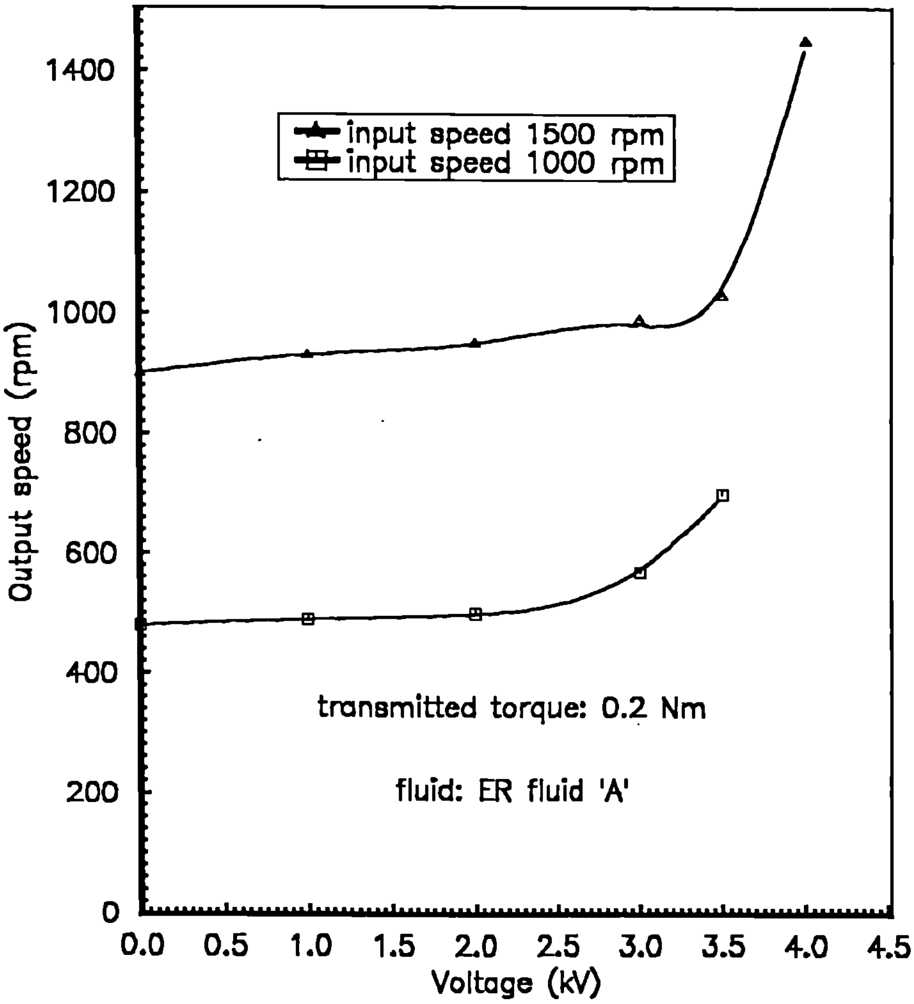

Figure 3.30: Constant torque characteristics of the ER coupling

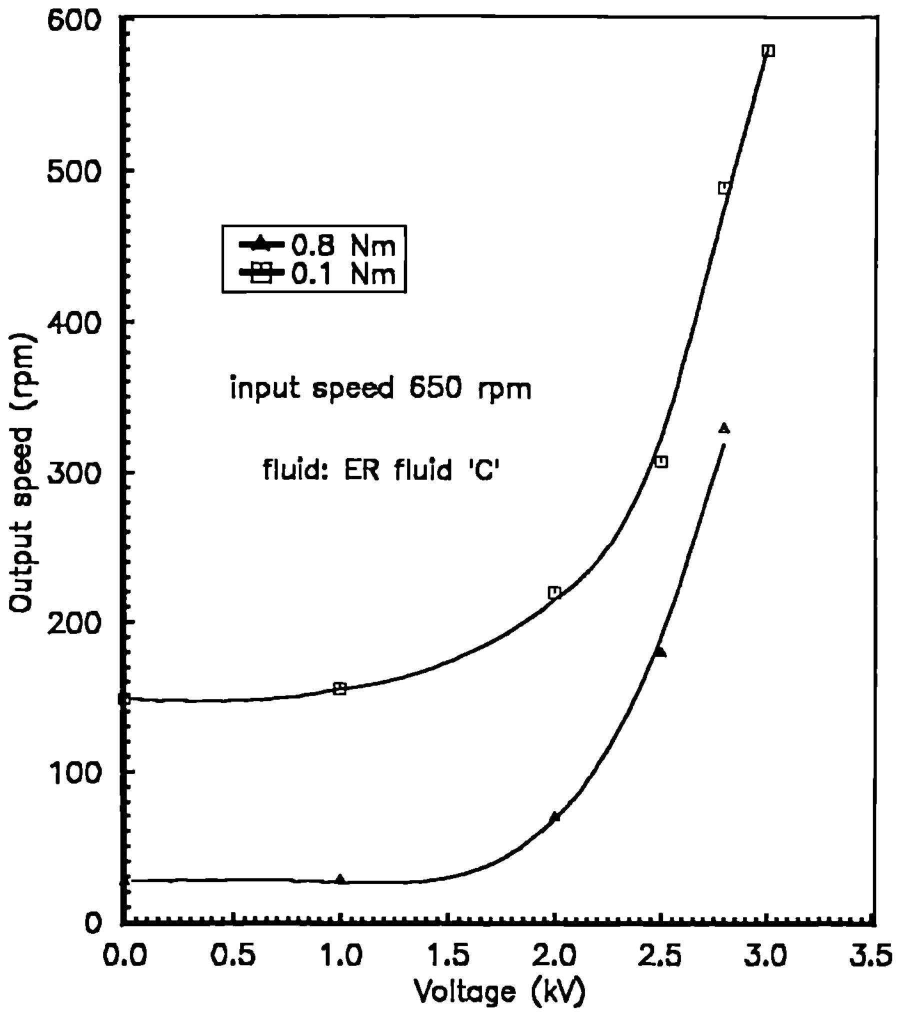

Figure 3.31: Constant torque characteristics of the ER coupling

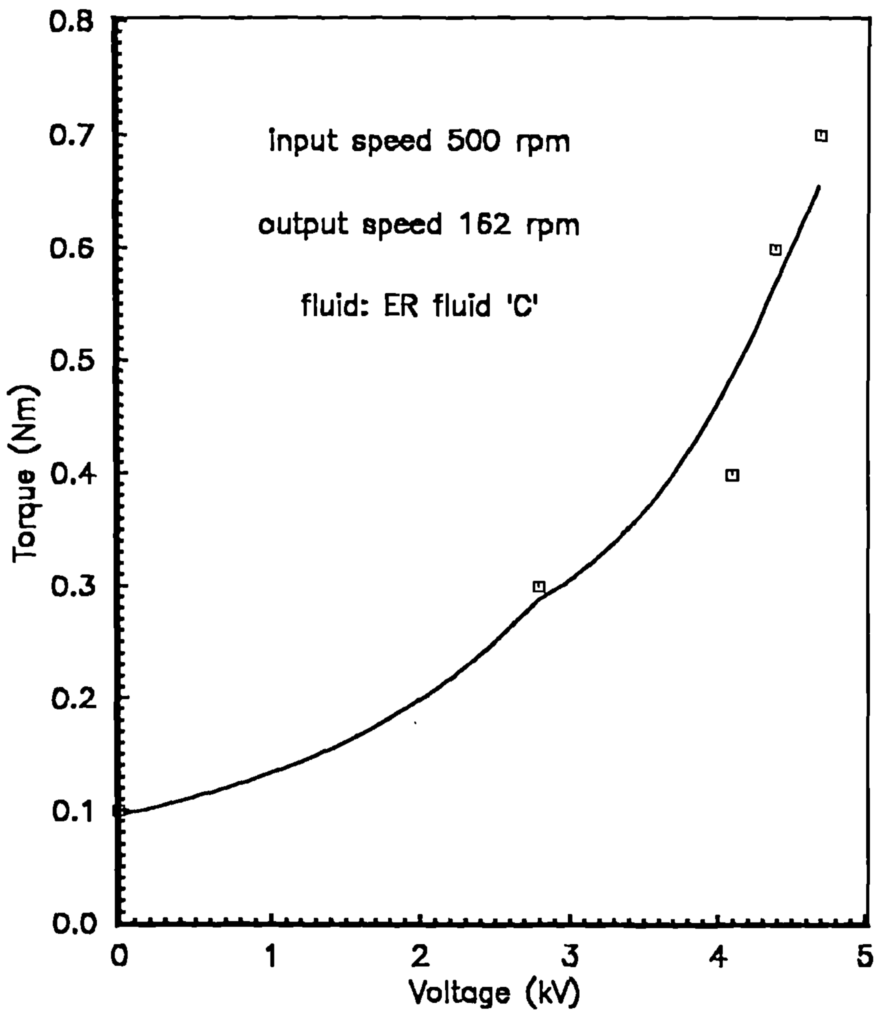

Figure 3.32: Constant speed ratio characteristics of the ER coupling

500 rpm and 162 rpm, respectively. The torques increases from 0.1 Nm to 0.72 Nm as the voltage increases from 0 to 4.6 kV.

It is understandable that alternating currents may have a different effect on the ER phenomenon than those obtained using direct currents. Figure 3.33(a) and (b) show respectively the results obtained with the "Brandenburg" DC voltage and with the 50 Hz AC voltage generator. It appears that a 50 Hz AC signal produces a better effect in the fluid than a DC signal. This result conflicts with that obtained by many previous investigators and with the theoretical analysis in Chapter 2. It should be noted that the two sets of results are not directly comparable because: a) the results obtained from the drive shaft are not accurately reproducible and b) the electric parameters for both of these cases are not exactly the same, namely the current passing through the ER fluid and the temperature in the fluid. Unfortunately, the current is not recorded during the tests because no reliable readings can be obtained.

It has to be pointed out that although the "Trek" system provides a sophisticated high voltage amplifier/supplier, the results obtained with different frequencies do not show any discernible trend. This can be explained by the fact that the readings of output speed and torque (as well as the excitation current) were randomly affected by the application of voltages to the drive shaft. However, some typical results are shown in Figure 3.34. It is not clear from the results which frequency is the most effective.

The drive shaft has demonstrated results which are difficult to reproduce. One of the reasons for this is that the gap between the electrodes is too small at 2 mm. If the gap between one pair of plates is somehow reduced to 1.5 mm, the next gap will be 2.5 mm, which leads to an error of $\frac{2.5-1.5}{2}=50\%$.

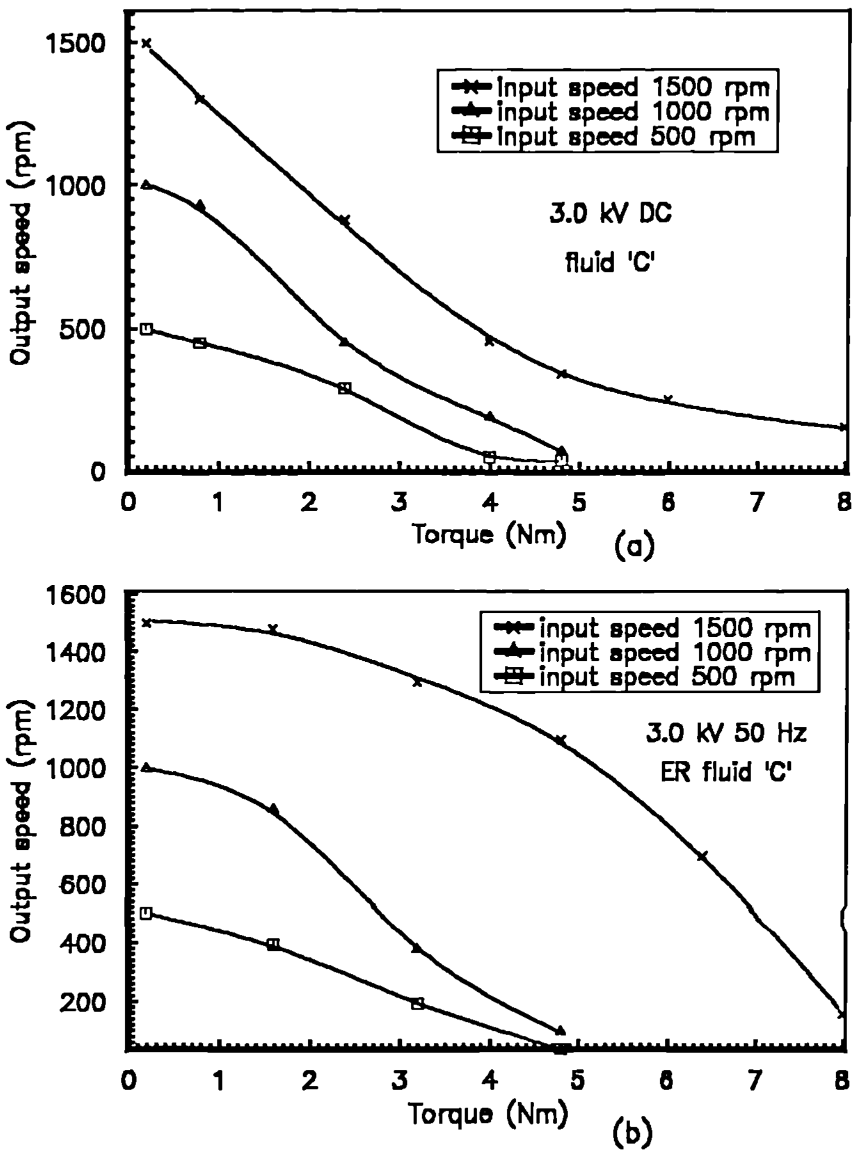

Figure 3.33: The influence of frequency on the ER effect

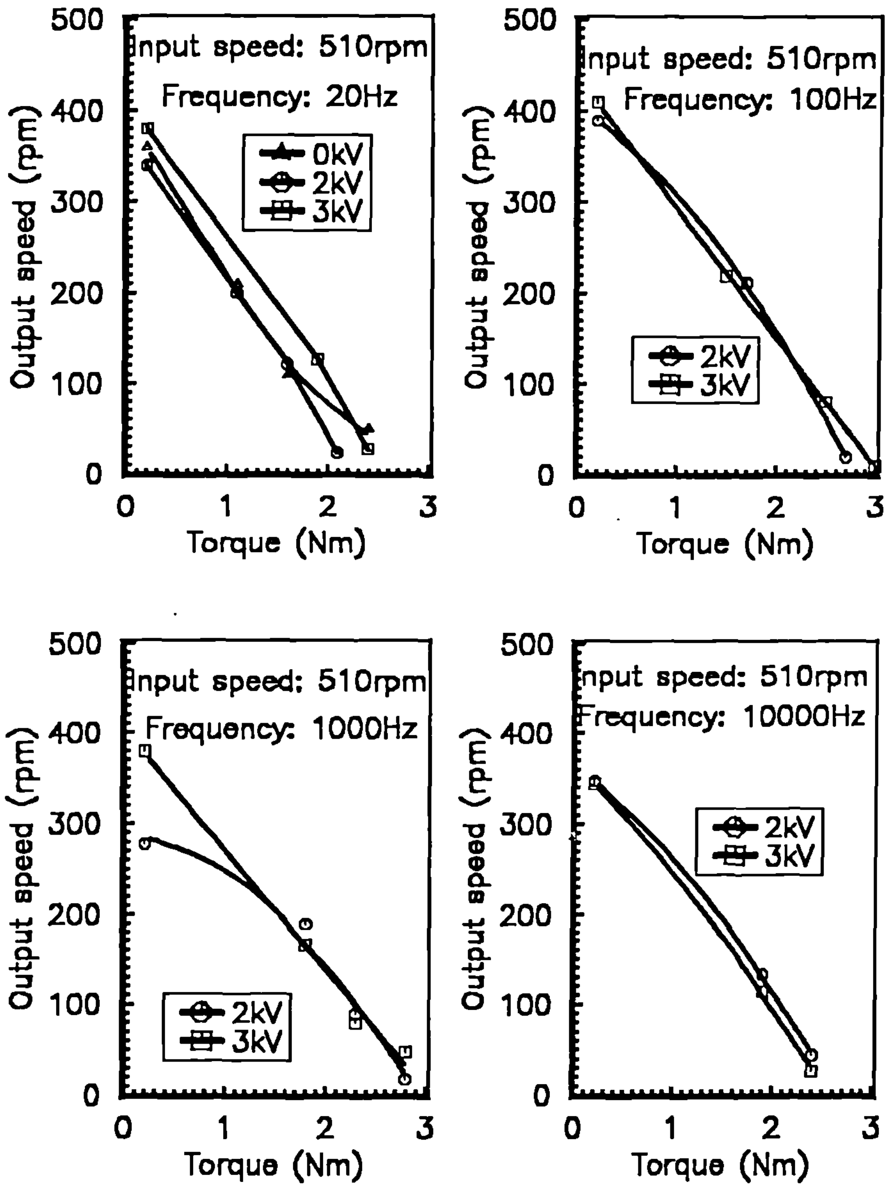

Figure 3.34: The influence of frequency on the ER effect

In fact, this level of uncertainty was observed during the assembly. Another reason is probably the difference in fluid temperatures for different tests.

It is noted that the fluids tested can only achieve up to 5 Nm in torque. This is much smaller than required. Better ER fluids are undoubtedly necessary.

3.6.5 Concluding Remarks

From the above results and discussion, the following conclusions can be drawn:

1. Over the speed range up to 1,500 rpm, the drive shaft is capable of providing continuously variable control of transmitted torque and output speed. A direct 1:1 drive is available at smaller transmitted torques. Constant torque and constant speed (or speed ratio) transmission is achievable by the control of voltage applied to the drive shaft.

2. Experiments on the influence of different frequencies on the ER effect failed to give conclusive results, due to the poor reproducibility of the drive shaft results and the problems with the data readings and excitation current.

3. The maximum transmitted torque level fell well short of that originally specified. However, given an ER fluid capable of sustaining a shear stress of around 15 kPa, the present concept of the drive shaft can readily be developed to meet the specification.

4. Further improvements in the structure of the drive shaft are required in order to reduce errors caused by the variation of the effective gap between electrodes.

CHAPTER 4

ELECTRORHEOLOGICAL MECHANICAL POWER TRANSMISSION

4.1 Introduction

In what follows in this Chapter, an electrorheological power transmission device, or ERPT, is a rotary device utilising the electrorheological shear developed between annular discs or cylinders to transmit a continuously variable speed and torque from a prime mover to a load.

The ERPT is, in fact, a kind of coupling, just like a hydrostatic or hydrodynamic coupling and hydroviscous drive. All these couplings have a shortcoming of low efficiency at low speed ratio (the ratio of output speed to input speed). However, when these couplings are combined with a gear train, a large portion of power can be arranged to be transmitted through the high efficiency mechanical gear, thus improving the efficiency of the whole system. Ideally, an ERPT should always operate at a relatively high speed ratio in order to provide better efficiency. To accommodate the requirements, there needs to be a combination of mechanical drives, i.e., mechanical gear trains, working in conjunction with the ERPT.

This chapter describes the combination of an ERPT with a fixed shaft gear box, whilst attention is concentrated on the analysis of the combination of ERPT with various planetary gear trains. It is shown that in principle electrorheological mechanical power transmissions possess advantages over existing ERPT's.

4.2 ERPT and Fixed Shaft Gear Trains

It is well known that gear transmission can achieve an efficiency of up to 98%. The introduction of a gear train into an ERPT provides an effective way of extending ERPT characteristics. Fixed shaft gear trains are usually arranged at the output end of the ERPT. To meet different requirements, two or more gears are necessary. Figure 4.1 shows an ERPT combined with a three-gear train. With the ERPT working at a relatively high speed ratio, a wide range of output speeds is available by selecting different gears. The following relationship exists with this arrangement.

$$n_2 = n_1 i_1 i_2 \tag{4.1}$$

where i_1 is the ratio of output speed to input speed in the ERPT and i_2 is that in the gear train. The terms n_1, n_2 represent, respectively, the input and output speeds of the transmission.

Also we can write

$$T_2 = \frac{T_1}{i_2} . \tag{4.2}$$

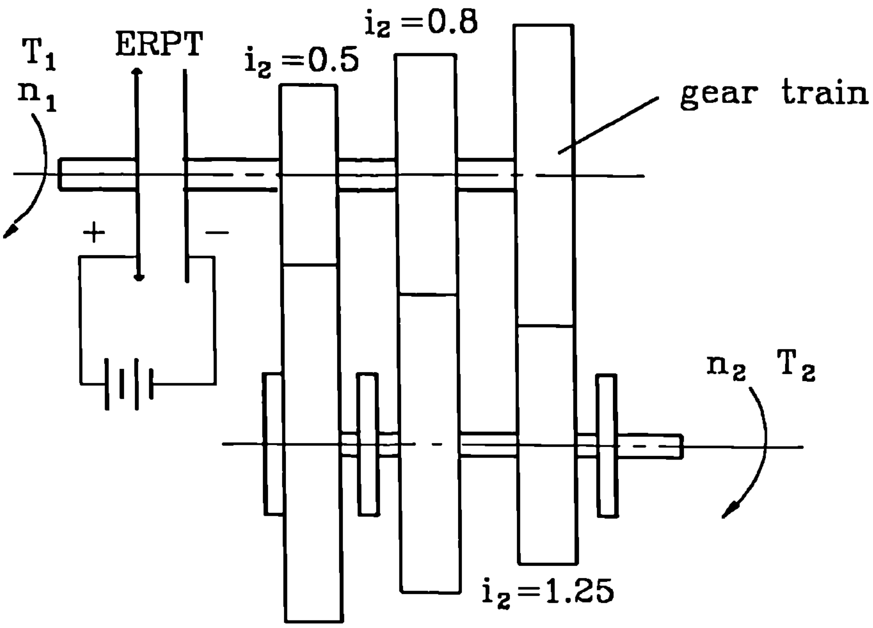

Figure 4.1: Schematic showing an ERPT combined with a three-speed gear train

To illustrate the use of equations (4.1) and (4.2), consider a numerical example in which

$n_1 = 1000\ rpm,\quad T_1 = 10\ Nm,\quad i_1 = 0.7\ to\ 1.0,\ and\ i_2 = 0.5,\ 0.8,\ and\ 1.25,$

Then the outputs will be:

$$n_2 = 350 - 500\quad rpm\quad when\quad i_2 = 0.5$$

$$n_2 = 560 - 800\quad rpm\quad when\quad i_2 = 0.8$$

$$n_2 = 840 - 1200\quad rpm\quad when\quad i_2 = 1.25$$

Transmitted torque will be increased or decreased accordingly. It is clear that a much wider range of output speed is achieved by selecting different gears to transmit the output of the ERPT's.

More significantly, power transmission efficiency is improved. For instance, if the ERPT alone is to provide an output speed between 350 and 500 rpm, the efficiency will be in the range 0.35 to 0.50. On the other hand, if the gear ratio 0.5 is selected in conjunction with the ERPT, efficiency will be within the range 0.66 to 0.95, because the gear efficiency is 0.95 or higher.

4.3 ERPT Combined with Planetary Gear Trains

4.3.1 Speed and Torque Relationships

Figure 4.2(a) and (b) show two examples of an ERPT combined with simple planetary gear trains. These arrangements can be generally described by Figure 4.2 (c) from which the properties of speed, torque and efficiency can be identified.

It is known [4] that planetary gear trains have the following speed relationship

$$n_1 + An_3 - (1 + A)n_2 = 0 \tag{4.3}$$

Because the planetary gear train possesses two degree of freedom, the following equations can be assumed:

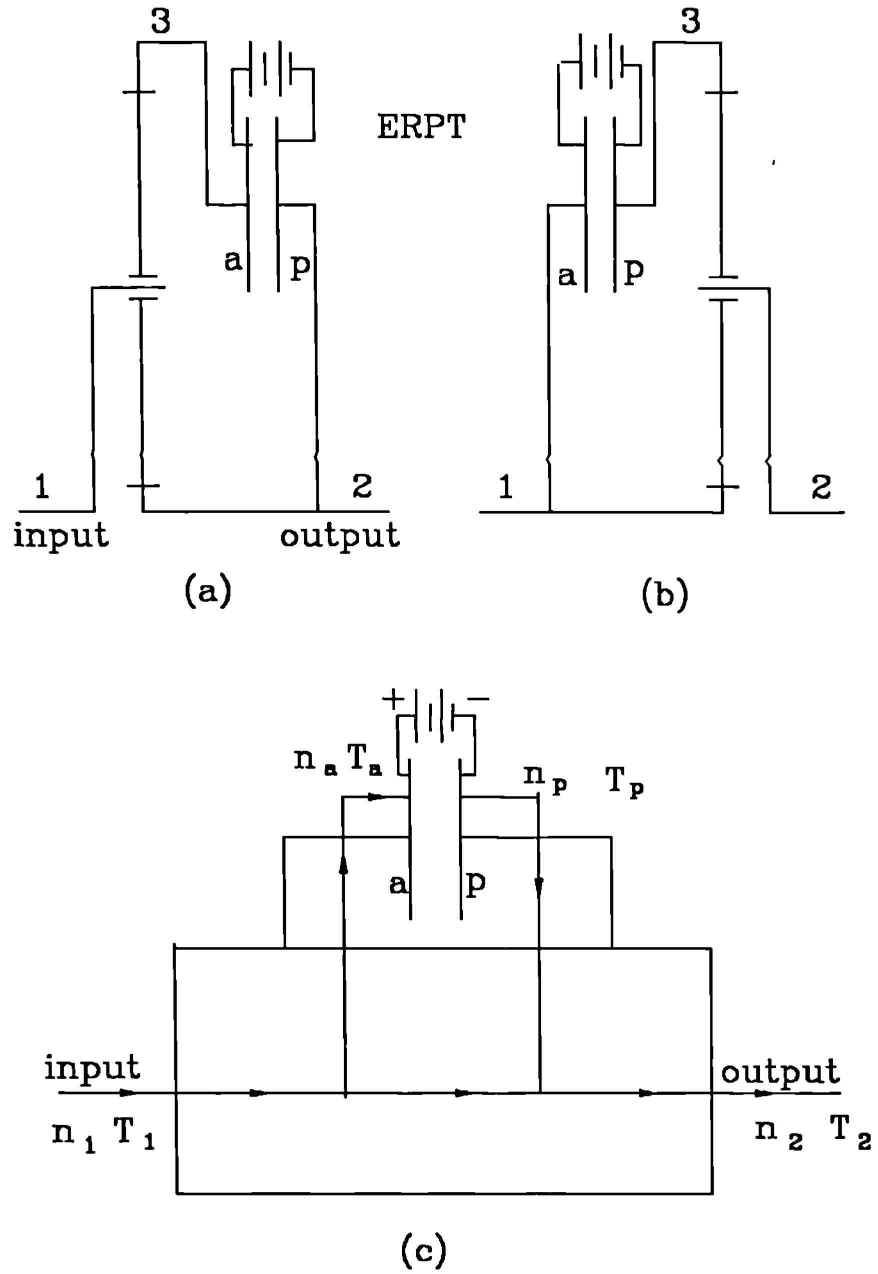

Figure 4.2: Schematic graphs showing ERPTs combined with planetary gear trains

$$n_a = e_1 n_1 + e_2 n_2 \quad (4.4a)$$

$$n_p = e_3 n_1 + e_4 n_2 \quad (4.4b)$$

or

$$n_1 = \frac{e_4}{e_1 e_4 - e_2 e_3} n_a - \frac{e_2}{e_1 e_4 - e_2 e_3} n_p \quad (4.5a)$$

$$n_2 = \frac{e_3}{e_2 e_3 - e_1 e_4} n_a - \frac{e_1}{e_2 e_3 - e_1 e_4} n_p \quad (4.5b)$$

where e_1, e_2, e_3, e_4 are parameters determined by the planetary gear train parameter A which is, in turn, determined by the parameter α which is the ratio of the number of teeth of the annulur gear to that of the sun gear. Figure 4.3 shows the relationship between A and α for different planetary gear trains. Therefore when a planetary gear train is designed, the parameters e_1, e_2, e_3, e_4 are automatically defined.

From a power balance point of view, the following relationship is obtained:

$$T_1 n_1 + T_2 n_2 + T_a n_a + T_p n_p = 0. \quad (4.6)$$

Combining equation (4.4) and (4.6) gives:

$$T_1 = -e_1 T_a - e_3 T_p \quad (4.7a)$$

$$T_2 = -e_2 T_a - e_4 T_p \quad (4.7b)$$

or

$$T_a = \frac{e_4}{e_2e_3 - e_1e_4} T_1 - \frac{e_3}{e_2e_3 - e_1e_4} T_2 \tag{4.8a}$$

$$T_p = \frac{e_2}{e_1e_4 - e_2e_3} T_1 - \frac{e_1}{e_1e_4 - e_2e_3} T_2. \tag{4.8b}$$

The following properties can then be derived from the above equations.

1. Speed ratios i_{21} *and* i_{pa}:

$$i_{21} = \frac{n_2}{n_1} = \frac{e_3 - e_1 i_{pa}}{e_2 i_{pa} - e_4} \tag{4.9a}$$

$$i_{pa} = \frac{n_p}{n_a} = \frac{e_3 + e_4 i_{21}}{e_1 + e_2 i_{21}} \tag{4.9b}$$

2. Torque ratio K_{21}: In couplings, input and output torques have the same amplitude but different direction, i.e., $\frac{T_p}{T_a} = -1$ therefore

$$K_{21} = \frac{-T_2}{T_1} = \frac{e_4 - e_2}{e_3 - e_1} \tag{4.10}$$

3. Efficiency η_{21}:

$$\eta_{21} = i_{21}K_{21} = \left(\frac{e_3 - e_1 i_{pa}}{e_1 i_{pa} - e_4}\right)\left(\frac{e_4 - e_2}{e_3 - e_1}\right) \tag{4.11}$$

4.3.2 Alternative Arrangements

There are basically two ways of integrating an ERPT with planetary gear trains: either with the gear train at the input side or alternatively at the output side.

There are twelve possible arrangements, six with the planetary gear train at input side, and six with the planetary gear train at the output side. These are shown in Figure 4.3. When the gear train is at the input side, the part p of ERPT is rigidly connected to the output shaft 2, and part a of ERPT is connected to the third element of the gear train, i.e., $n_3 = n_a$., We then have:

$$e_1 + e_2 = 1, \quad e_3 = 0, \quad e_4 = 1$$

and

$$n_1 + An_a - (1 + A)n_2 = 0 \tag{4.12}$$

Comparing equation (4.12) with (4.5a) yields:

$$e_1 = -\frac{1}{A}, \quad e_2 = 1 - e_1 = 1 + \frac{1}{A}$$

Thus the different properties are rewritten as:

$$n_1 = \frac{n_a + (e_1 - 1)n_p}{e_1}, \quad n_2 = n_p \tag{4.13}$$

$$T_1 = -e_1 T_a, \quad T_2 = -(1 - e_1)T_a - T_p \tag{4.14}$$

$$i_{21} = \frac{e_1 i_{pa}}{1 - (1 - e_1)i_{pa}}, \quad K_{21} = -1, \quad \eta_{21} = i_{21} \tag{4.15}$$

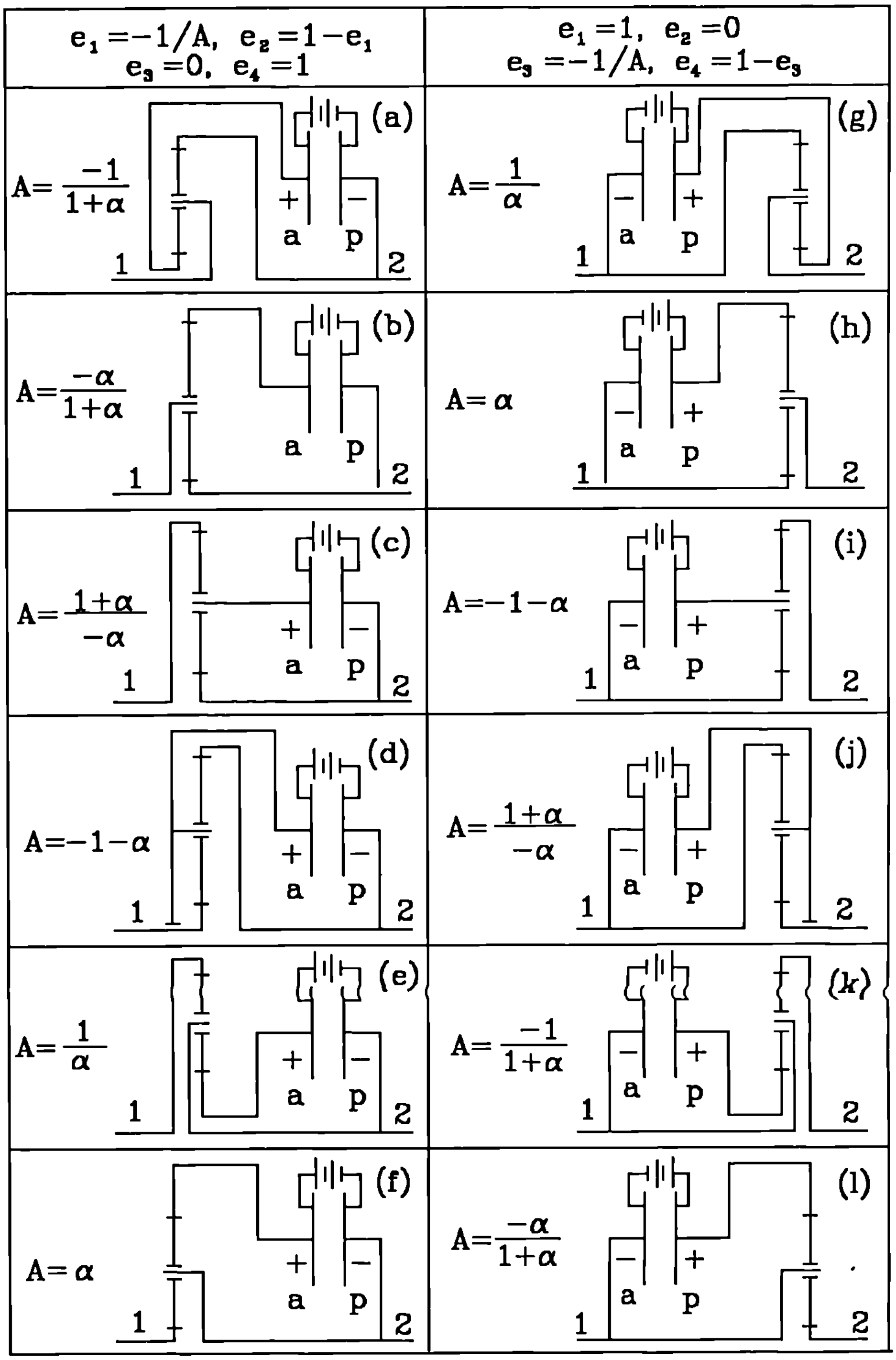

Figure 4.3: Different arrangements of ERPTs combined with planetary gear trains

Similarly, when the gear train is at the output side, the four parameters will be:

$$e_1 = 1, \quad e_2 = 0, \quad e_3 = -\frac{1}{A}, \quad e_4 = 1 + \frac{1}{A}$$

Thus

$$n_1 = n_a, \qquad n_2 = \frac{n_p - e_3 n_a}{1 - e_3} \tag{4.16}$$

$$T_1 = -T_a - e_3 T_p, \qquad T_2 = (e_3 - 1)T_p \tag{4.17}$$

$$i_{21} = \frac{i_{pa} - e_3}{1 - e_3}, \qquad K_{21} = -1, \qquad \eta_{21} = i_{21} \tag{4.18}$$

However, it should be noted that in simple planetary gear trains, the structure parameter α must satisfy the inequality $1.4 \leq \alpha < 4.0$, because of their construction limitation.

From calculations using the above equations, it can be shown that only arrangements a, b and g, h are economically and practically viable. Figure 4.4 shows the speed and efficiency characteristics of the four arrangements. In these, only part of the power is transmitted through the low efficiency ERPT, whilst the remaining part is transmitted through the highly efficient planetary gear trains. This means that we can use a small power ERPT in combination with a large power mechanical drive to yield a new variable speed transmission device. Furthermore, a direct drive ($i_{21} = 1$) can be obtained by locking up the ERPT and a purely mechanical drive can also be obtained by braking the third element of the planetary gear train.

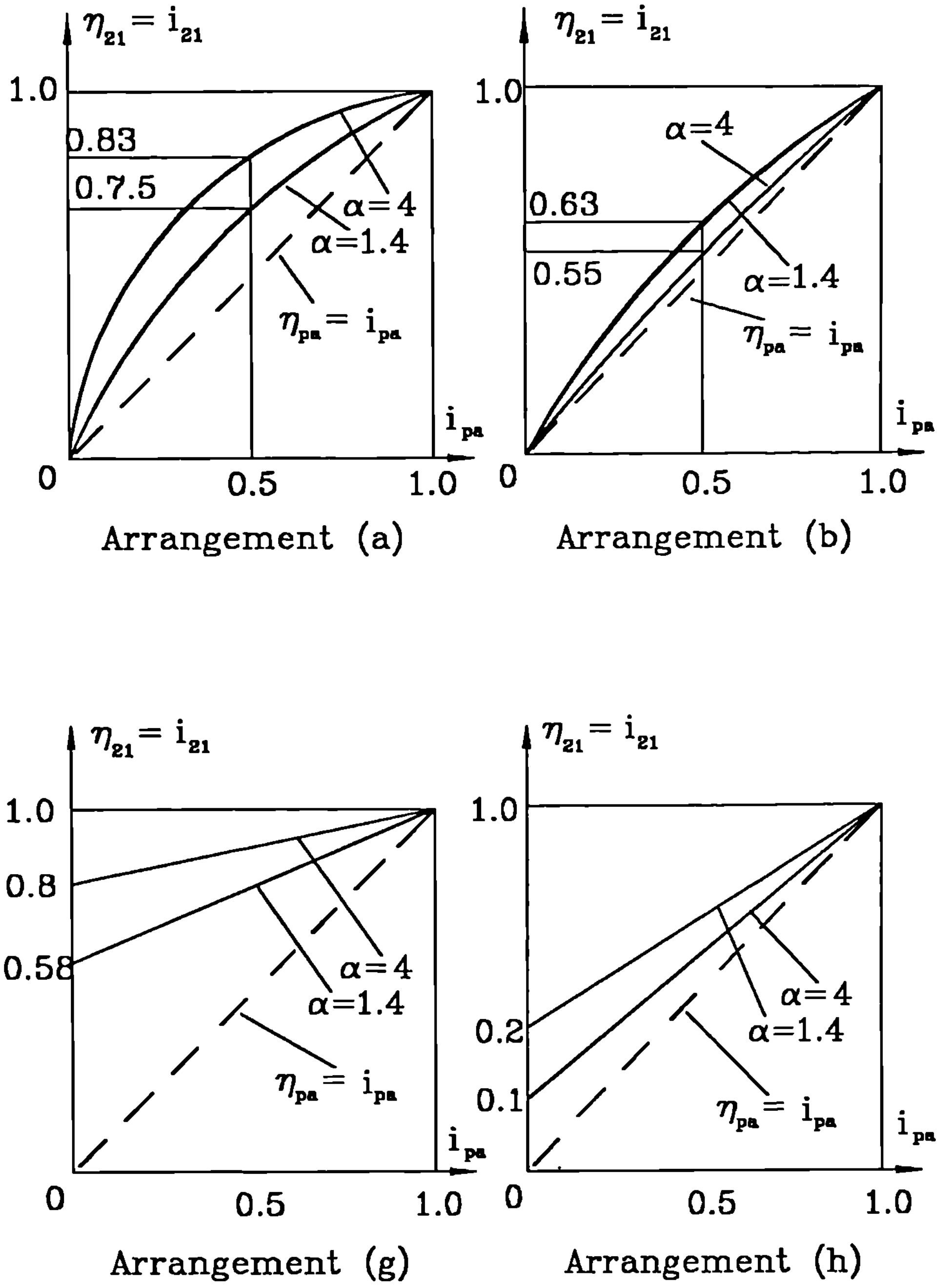

Figure 4.4: Different arrangements of ERPTs combined with planetary gear trains

4.3.3 Numerical Example

The arrangement shown in Figure 4.5a is taken as an example to illustrate the performance of the electrorheological mechanical transmission. Let $\alpha = 3$, *then* $A = -\frac{1}{1+\alpha} = -\frac{1}{4}$, $e_1 = -\frac{1}{A} = 4$.

4.3.3.1 Speed Characteristics

When the ERPT works as a variable speed modulator, that is, $0 \leq i_{pa} < 1.0$, the arrangement works as a variable speed drive, i.e., $i_{21} = \frac{4i_{pa}}{1 + 3i_{pa}}$. When the ERPT is locked up, that is $i_{pa} = 1.0$, a direct drive is achieved. When the third element is braked, a mechanical drive is obtained, which has a speed ratio

$$i_{21} = \frac{n_2}{n_1} = \frac{1+\alpha}{\alpha} = 1.33$$

These are shown in Figure 4.5b.

4.3.3.2 Torque Characteristics

When the ERPT works as a variable speed modulator, $T_1 = -T_2 = -e_1T_a$, that is, the torque transmitted is e_1 times as large as that transmitted through the ERPT itself. When the ERPT is locked up, the arrangement transmits the maximum torque and when the third element is braked, the output torque is given by $T_2 = -T_1/i_{21}$. The torque characteristic is shown in Figure 4.5c.

The efficiency of the whole arrangement is obviously higher that that of the ERPT itself. This example illustrates the advantages of electrorheological mechanical power transmission.

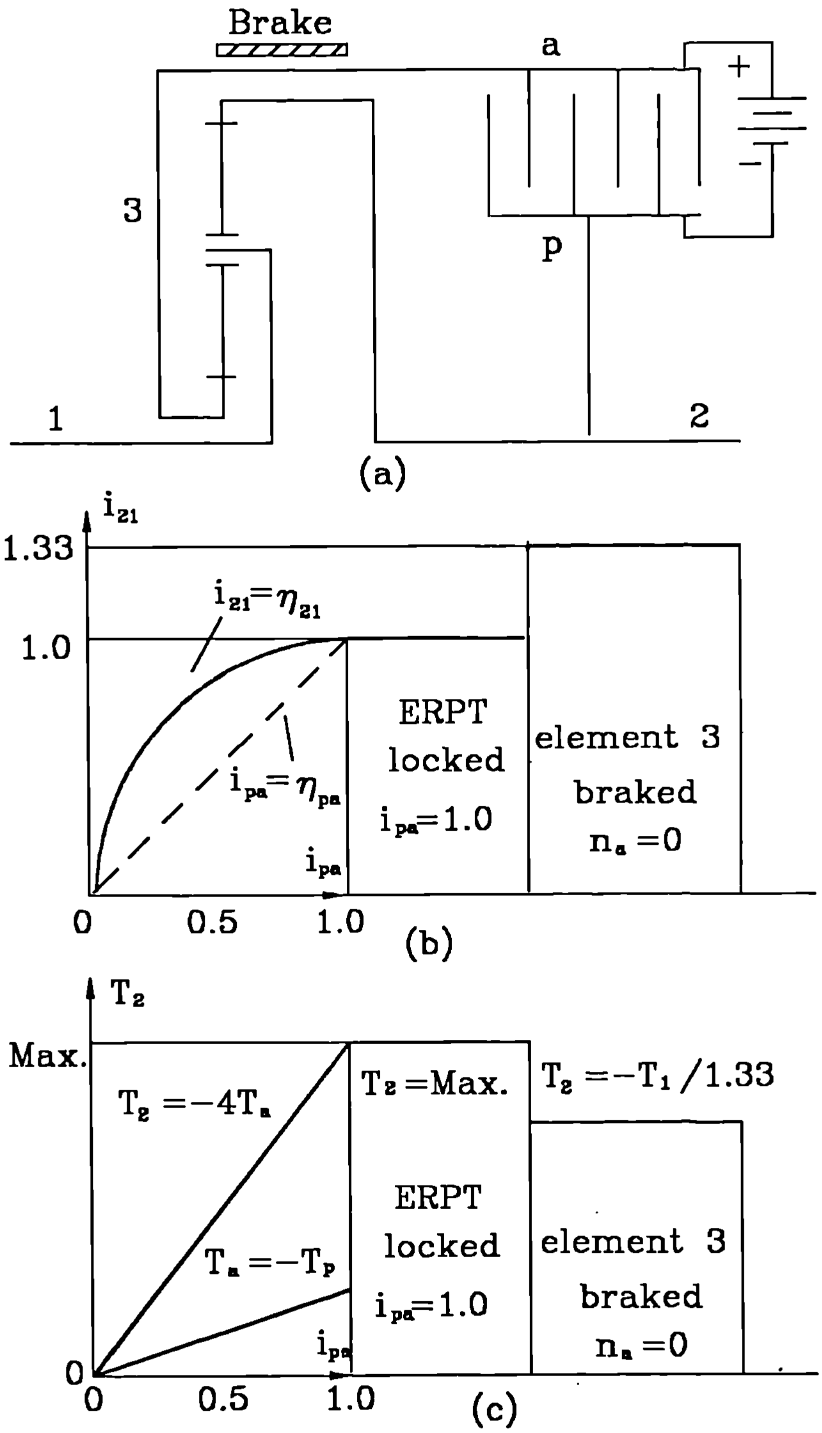

Figure 4.5: Characteristics of an elcctrorheological mechanical power transmission

4.4 Summary of Chapter 4

From the above analysis, the following conclusions can be drawn:

1. Although an ERPT can achieve a continuously variable speed transmission, it has the disadvantage of low efficiency at low speed ratios.

2. An electrorheological mechanical power transmission has all the merits of an electrorheological power transmission.

3. By combining an ERPT with a fixed shaft gear box, a wide range of variable output speeds can be achieved, whilst the efficiency of the transmission is much improved.

4. By combining an ERPT with a planetary gear train, a large proportion of the power can be arranged to be transmitted through the highly efficient gear train. Thus the overall efficiency is improved.

CHAPTER 5

ELECTRORHEOLOGICAL DAMPER FOR ADAPTIVE SUSPENSION

5.1 Introduction

Suspension systems are widely used in machines, structures and especially in vehicles. Vehicle vibrations may cause damage to the vehicle itself and vibrations at a frequency in some particular range may cause severe discomfort to the driver[115]. Therefore, it is essential that vehicle vibrations are controlled to achieve driving smoothness and comfort.

Most vehicles are installed with passive suspension systems which are designed for the most common road surface conditions or an intended condition, such as an agricultural field. Conditions are often variable, particularly for military vehicles and other off-road vehicles, and a passive suspension cannot provide satisfactory performance. Thus there is considerable pressure on motor vehicle manufacturers and component suppliers to develop suspension systems which provide better handling and/ or ride quality than the conventional suspension systems.

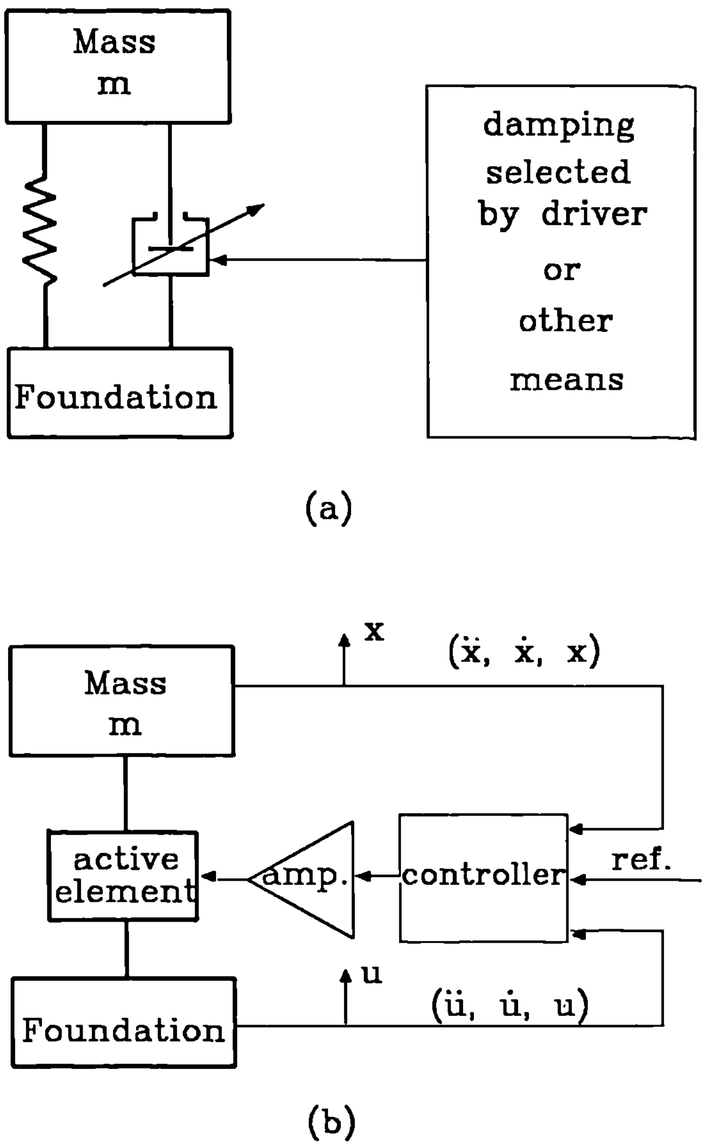

Figure 5.1: Schematic graphs showing variable passive (a) and active (b) suspensions

Some semi-active suspension systems [116] have been developed and applied on vehicles. This kind of suspension provides a range of damping settings for the shock absorber, either through selection by the driver or by some other way of selection. This is shown schematically in Figure 5.1(a). Some more sophisticated active suspensions are under development. An active suspension can change its damping coefficient to meet different vibration conditions by means of servo control, as shown schematically in Figure 5.1(b). Most active suspensions employ hydraulic servo control systems for modulation. Automotive Engineer [117] recently reported an active suspension system which is schematically shown in Figure 5.2. The hydraulic servo control system, which is designed to stimulate a damped spring for a racing car, is driven by a pump. Displacements and accelerations are measured and processed to form generalised displacement demands which are converted to actuator position demands and compared with actual displacements to form servo-valve drive currents. Thompson [118] theoretically investigated active suspensions based on electrohydraulic control systems.

Active suspensions controlled by hydraulic systems could be very bulky and expensive. The appearance of the electrically-active ER fluid makes a practically economic adaptive suspension possible. The damping in the ER adaptive suspension system can be continuously changed by the control of electric field applied across the fluid. Figure 5.3 schematically shows the principle of a single degree of freedom ER adaptive suspension system.

Klass [24] and Bullough [33] investigated ER dampers in the 1960's and 1970's. Stanway, Sproston and Stevens [84,85] achieved encouraging results with their prototype ER damper at Liverpool University.

This chapter provides a theoretical and experimental analysis of the ER suspension system. It shows that when the mass fraction of the dielectric particles to that of the base oil is less than or around 1:5, the damping behaviour

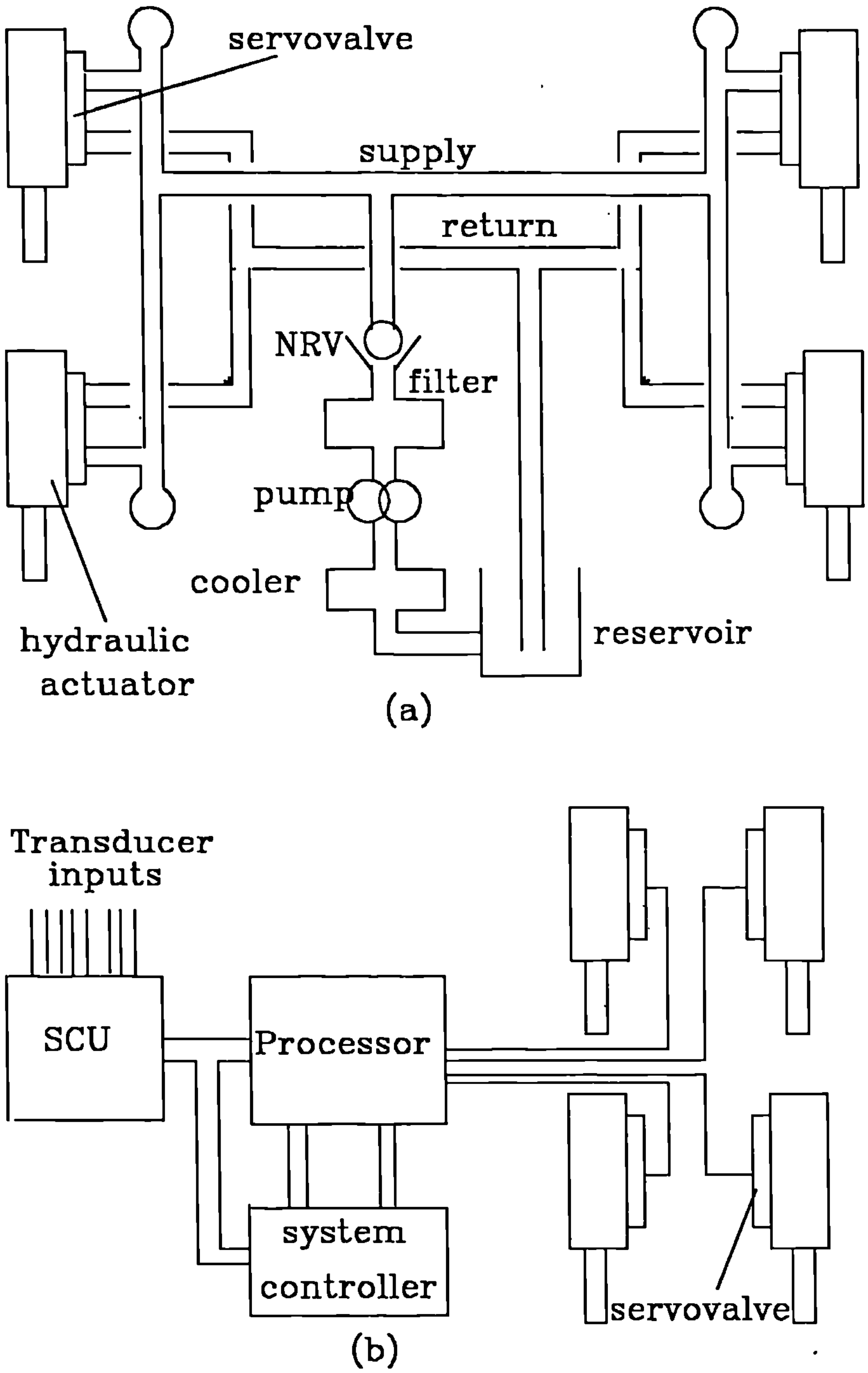

Figure 5.2: A hydraulic control system for an active suspension

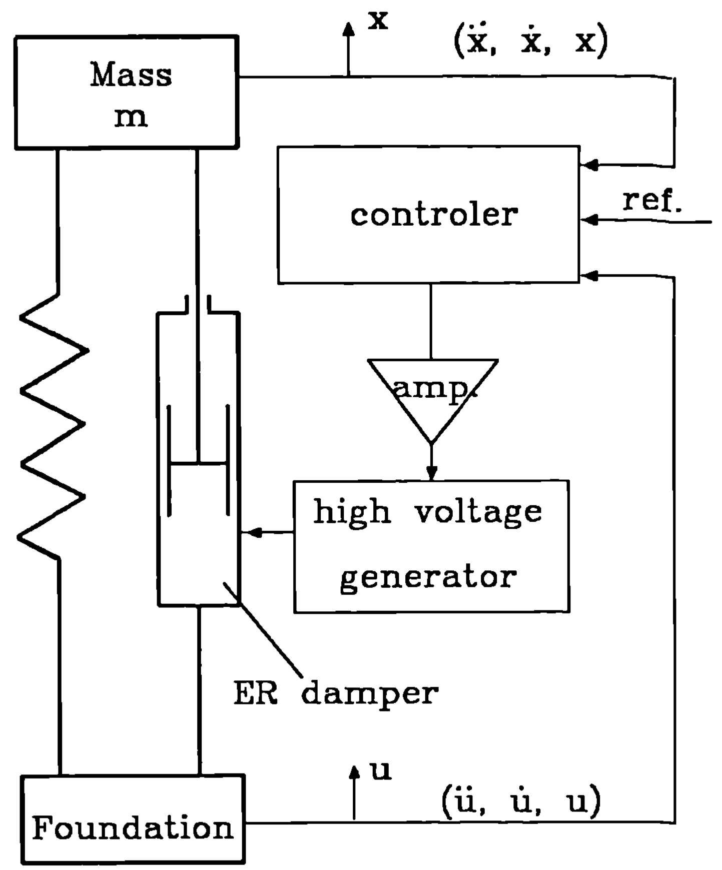

Figure 5.3: An adaptive suspension system using an ER damper

of the ER fluid can be expressed as viscous damping. The theoretical and experimental analyses indicated that an ER damper could be developed for practical vehicle applications.

5.2 Principle of ER Damping

5.2.1 ER Phenomenon and Apparent Viscosity of ER fluid

As indicated in Chapter 2, an electrorheological fluid is one in which some dielectric particles are suspended in an insulating base oil. When the voltage applied to the fluid increases, its apparent viscosity increases because of the formation of particle chains in the electric field.

When ER fluids are used as damping media in shock absorbers, the damping characteristics of the fluid can be changed simply by changing the voltage. The fluid passes a very small current (usually within a few mA), due to the dielectric property of the base oil, and therefore the electric power needed to control the damper is small (within a few watts). Note that the process of the electrorheological effect is totally reversible.

5.2.2 Coulomb Damping and Viscous Damping

When the ER fluid is used as damping medium in a damper, it is important to specify which kind of damping the ER damper exhibits. It was indicated in some early research [84] that at low electric field strengths (less than 0.5kV/mm) an ER damper behaves like a viscous device whilst at higher field strengths (greater than 2kv/mm), the damping force behaves more like Coulomb friction than viscous friction. It was also reported in [33] that Coulomb friction plays an important role in the ER damper.

Physically, Coulomb damping is like dry friction which occurs when two surfaces are arranged to slide one upon another with a constant normal force holding them together [119]. If the particle mass ratio of an ER fluid is high, say, more than 1:1, the fluid becomes a kind of glue instead of a real solid when it is fully electrically stressed. Obviously, it will not behave like a Newtonian fluid and there is some Coulomb damping effect in it. Thus the ER damping is essentially Coulomb damping but with an element of viscous damping.

However, if the Coulomb damping parameter is very small, that is when the dry friction force is much smaller compared with the other forces applied to the mass, then the Coulomb damping is negligible. Low particle mass ratio ER fluids did not solidify at the maximum field strength because of the amount of base oil, and behave more like viscous fluids. In this case the ER damping can be treated as viscous damping. The experimental results shown in Figure 5.8 indicate that if the fluid is of large particle mass ratio, ER damping is mainly viscous at low voltage, whilst at high voltage the damping is mainly due to Coulomb friction. On the other hand, Figure 5.9 shows a different result: if the particle mass ratio is 1:5, the ER damping is mainly viscous for all applied voltages. Therefore, the damping performance of an ER fluid depends on both the fluid itself (carrier, particle and mass ratio) and also on the electric field strength.

5.2.3 Equation of Motion

As most ER damping in practical applications can be represented by viscous damping, the equation of motion considered here will be only for the viscous situation. There are many different designs for ER dampers. The concentric cylindrical type and plate type are two of them, as shown in Figure 5.4 and

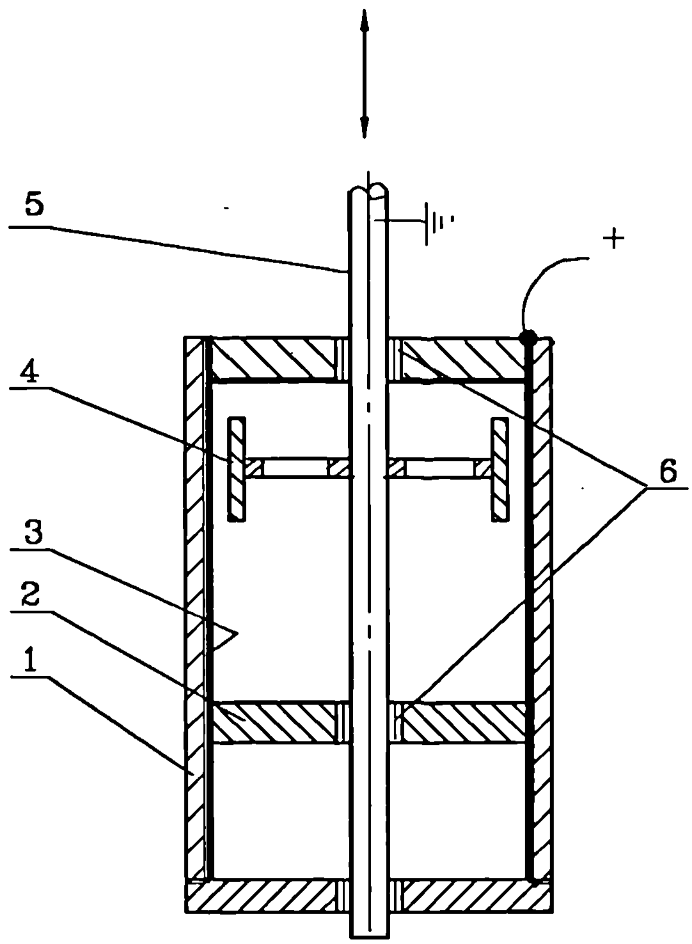

Figure 5.4: A cylindrical ER damper 1.Casing, 2.Plunger support, 3.Live surface, 4.Cylinder, 5.Plunger, 6.Seal and bearing

Figure 5.5. However, only the cylindrical type is considered in the following discussion.

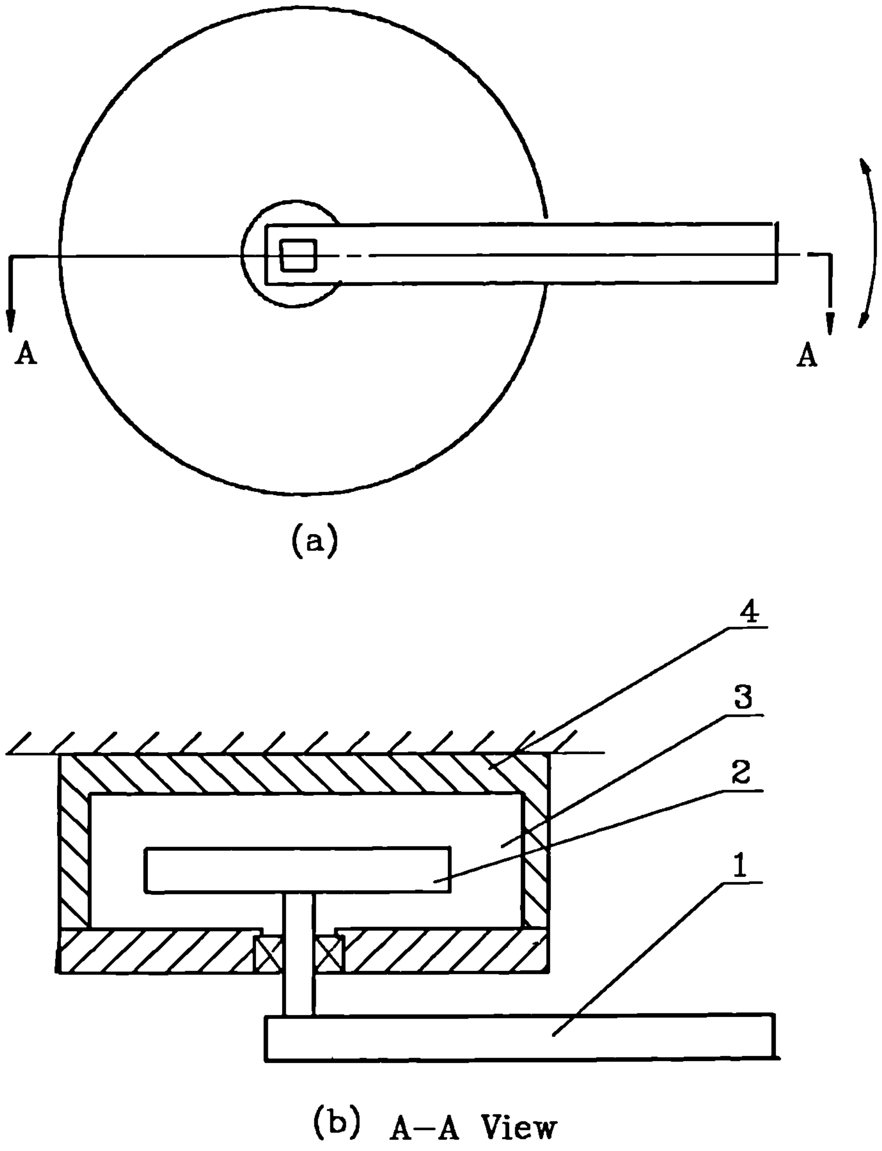

Figure 5.5: A disk type ER damper 1.Lever, 2.Live plate, 3.Fluid chamber, 4.Casing.

In Figure 5.6, when the cylinder is filled with ER fluid and the casing is stationary, and the viscous friction on the piston which is moving with velocity $\dot{x}$ is:

$$F_{ev} = \tau_1 A_1 + \tau_2 A_2. \tag{5.1}$$

Usually the gap between the electrodes $(r_2 - r_1)$ is small (between 1 and 5 mm) so as to limit the applied voltage between the electrodes. Thus it can be supposed that $\tau_1 = \tau_2 = \mu \dfrac{\dot{x}}{\frac{r_2 - r_1}{2}}$ [120], i.e.,

$$F_{ev} = 4\pi l \mu \dot{x} \frac{r_2 + r_1}{r_2 - r_1}. \tag{5.2}$$

For the case of several concentric cylinders:

$$F_{ev} = 4\pi l \mu \dot{x} \sum_{k=0}^{n} \frac{r_{k+1} + r_{k+2}}{r_{k+2} - r_{k+1}} \tag{5.3}$$

There exists another force on the piston due to the pressure difference between the two ends of the cylinders. However, this force is negligible compared to the viscous force. Therefore, in a single degree of freedom system with an ER damper as the damping element, the equation of motion can then be written as follows:

$$m\ddot{x} + (4\pi l \mu \sum_{k=0}^{n} \frac{r_{k+1} + r_{k+2}}{r_{k+2} - r_{k+1}})\dot{x} + kx = F \sin \omega t. \tag{5.4}$$

Let the damping coefficient c= $4\pi l\mu \sum_{k=0}^{n} \frac{r_{k+1} + r_{k+2}}{r_{k+2} - r_{k+1}}$ equation (5.4) then becomes

$$m\ddot{x} + c\dot{x} + kx = F \sin \omega t \tag{5.5}$$

The dynamic magnification [121] which is the displacement amplitude X divided by the static deflection $x_{st} = \frac{F}{k}$ then gives:

$$\frac{X}{x_{st}} = \frac{1}{(1 - \omega^2/\omega_n^{\ 2})^2 + (2c\omega/\omega_n)^2}$$

$$= [(1 - \frac{\omega^2}{\omega_n^{\ 2}})^2 + (8\pi l\mu \frac{\omega}{\omega_n} \sum_{k=0}^{n} \frac{r_{k+1} + r_{k+2}}{r_{k+2} - r_{k+1}})^2]^{-1} \tag{5.6}$$

5.3 ER Damper and Adaptive Suspension

As shown in Figure 5.3, the ER damper is used as a damping element in a single degree of freedom system. If the damping coefficient of the ER damper can be modulated so as to adaptively change to fit the desired requirement, then the damper can be made to approximate the behaviour of an active element. The damping coefficient of the adaptive element is controlled according to the comparison of the desired displacement and acceleration with the actual displacement and acceleration.

To make an ER damper into a practical adaptive element, suitable closed-loop control strategies are needed. The damping changes due to the change of the ER effect in the fluid. It is known that the response time of the ER effect is a few milliseconds [2].

5.4 Mechanical Design of ER Dampers

As cylindrical dampers are popularly used in practical applications, the following discussion concentrates on the mechanical design of cylindrical type ER dampers. Actually, torsional dampers are similar to the ER couplings which have been discussed in chapter three.

In ER dampers, the insulation arrangement is the same as for ER couplings. As shown in Figure 5.6, the seal arrangement is simpler than that of ER coupling, as only two 'O' ring seals are necessary to prevent the fluid leaking out of the casing.

The most complicated part is the piston since in practice more than one working surface is needed for the achievement of sufficient damping forces. Figure 5.6 illustrates an ER shock absorber, in which the piston is shown in detail. Three shear surface are formed by arranging four cylinders (6,7) coaxially. The cylinders are alternatively charged live or earth. The cylinders ends are incorporated in PTFE insulators (8) which prevent the live and earthed cylinders from touching. Alternate cylinders are connected to live or earth. The central plunger (1) acts as a connection for the earthed electrode in which the live electrode (13) is accommodated and wrapped by an insulator (12). When the piston moves, the ER fluid can pass the cylinders through the openings at the top and bottom of the piston. The whole piston

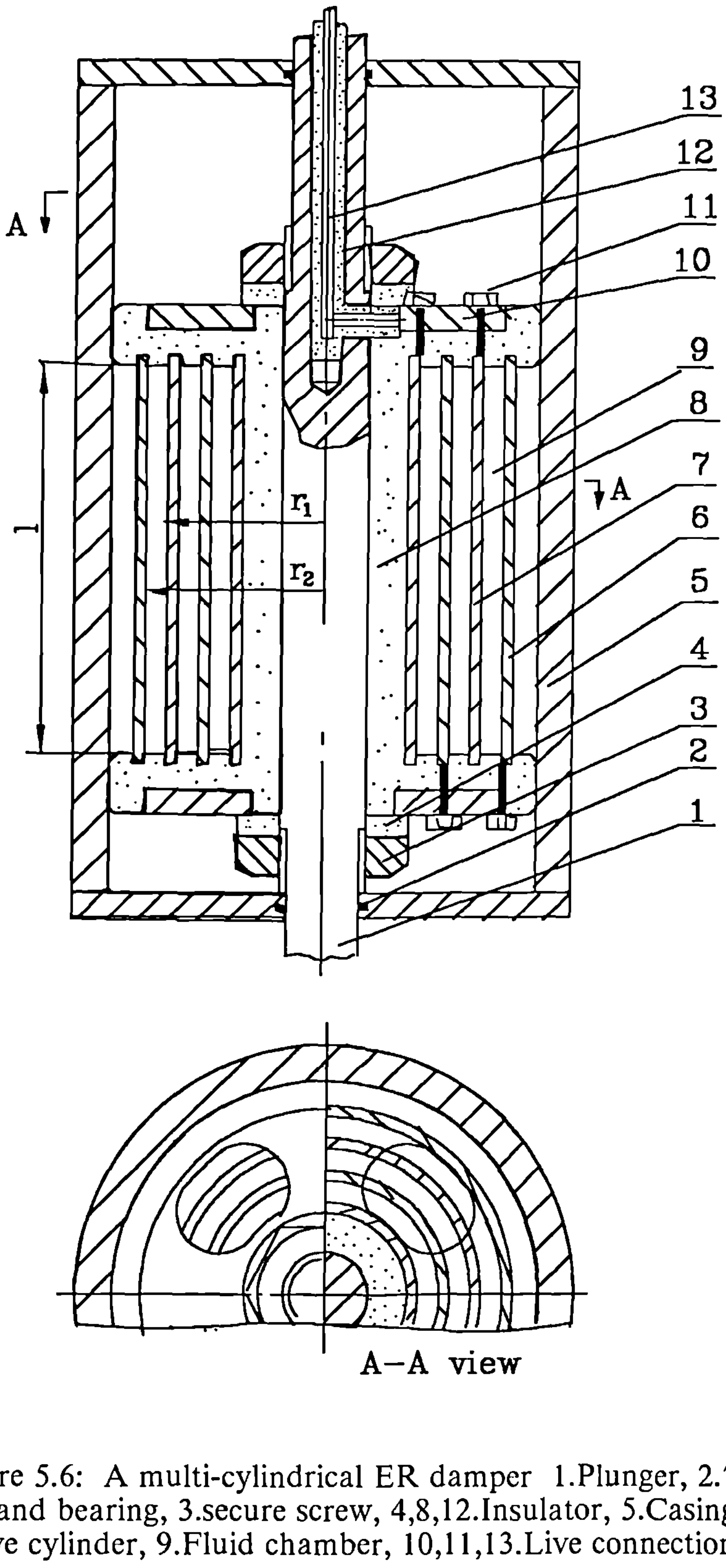

Figure 5.6: A multi-cylindrical ER damper 1.Plunger, 2.'O' ring seal and bearing, 3.secure screw, 4,8,12.Insulator, 5.Casing, 6.Earthed cylinder, 7.Live cylinder, 9.Fluid chamber, 10,11,13.Live connection

is free to move up and down in the casing (5) by the constraint of two bearings and seals (2).

There are three ways to change the damping characteristics of the damper: to use different ER fluids, to change the length of and gap between the cylinders and to change the voltage applied to the device. When an ER damper is designed and an ER fluid is chosen, it is the voltage which is modulated to achieve variable damping characteristics.

5.5 Experimental Investigation of an ER Damper

Although an ER damper can be designed and used as an adaptive damping element for adaptive suspension systems, a servo control system is needed for the purpose to be realised. Unfortunately, the experiment described here is unable to incorporate the control of a servo system. Therefore the experiment is designed to test the damping dependence on applied voltage, instead of testing a fully adaptive suspension system. The ER damper is controlled manually in a single degree of freedom system.

5.5.1 Experimental Arrangement

The damper was fitted to a commercially-available single degree of freedom vibration test facility, as shown in Figure 5.7. The mass (4) of 3.6 kg is driven through the coil spring (2) of stiffness 1.22 kN/m by a harmonic displacement input generated by the rotation of an eccentric disc (3). The frequency of the

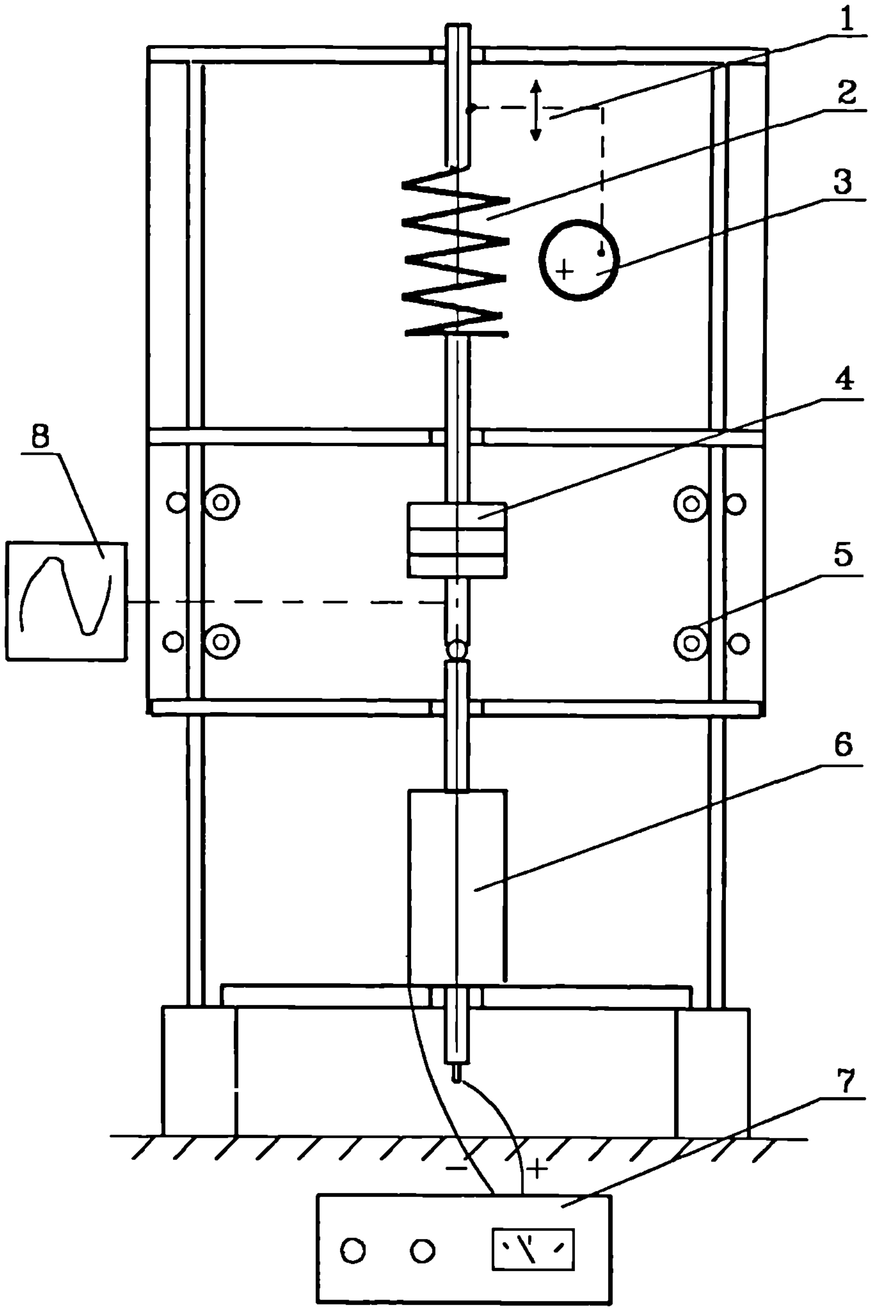

Figure 5.7: Schematic of ER damper test rig 1.Excitation, 2.Spring, 3.Eccentric disk, 4.Mass, 5. Roller, 6.ER damper, 7.High voltage generator, 8.Pen recorder.

input signal can be varied from zero to 5 Hz by controlling the rotational speed of the DC motor which drives the eccentric disc.

The mass is constrained to vibrate in the vertical direction and is connected to the brass plunger of the ER damper. The casing of the damper is connected firmly to the base of the test rig so that the casing is stationary when the piston of the damper is vibrating.

The displacement of the damper is measured with a pen recorder (8). The high voltages are supplied by the "Brandenburg" high voltage generator described in Chapter 3.

5.5.2 Experimental Procedure

Before the damper was fitted to the test rig, each working part of the damper was cleaned with acetone and then dried. The following steps are then carried out:

1. The damper (without ER fluid) was fitted to the rig to assess the performance without damping. The displacement was recorded for different frequencies in the range 0.5 Hz to 5 Hz.

2. ER fluid 'E', of small viscosity (mass ratio 1:5), was then introduced into the chamber of the damper. The damper was allowed to cycle for a few minutes in the frequency range 0.5 Hz to 5 Hz without applied voltage, to minimise any chance of partial sedimentation.

3. Still at zero voltage, the vibration frequency was increased from 0.5 Hz to 5 Hz in steps of 0.5 Hz. This procedure was then repeated for voltages of 1.0 kV to 4.0 kV.

4. Fluid 'E' was replaced by fluid 'F' which is of much larger viscosity (mass ratio 1:1). Steps 2 and 3 were repeated.

5.6 Experimental Results and Discussion

The above recorded displacements were plotted against frequency to show how the damping characteristics change with voltage. Figure 5.8 shows the results with fluid 'F' which has a particle to base oil mass ratio 1:1. It is clear that increasing the voltage increased the damping coefficient of the damper; however the range of damping available is not wide. Referring to Figure 5.8, it can be seen that the displacement curves do not coalesce at zero frequency. This is a typical evidence of Coulomb damping. Thus the damping is a combination of Coulomb damping and viscous damping. Consequently, it can be inferred that the ER fluid in this case is solidified to a large extent.

The results with fluid 'E', which has a mass ratio of 1:5, are very different to those with fluid 'F', as shown in Figure 5.9. It can be seen that the traces tend to coalesce at zero frequency. Thus the damping characteristics with this ER fluid are typically viscous. It is clear that the range of the damping change is very large. This is due to the low mass ratio and the consequent low unstressed viscosity of fluid 'E'.

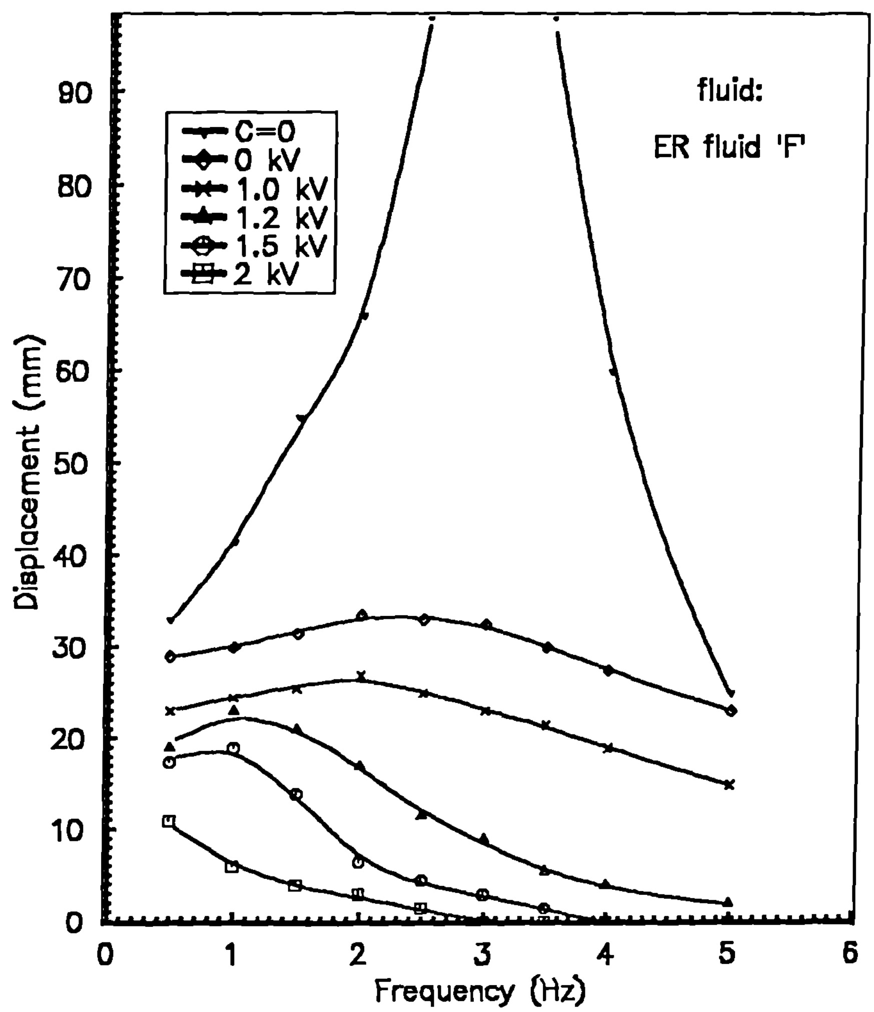

Figure 5.8: Experimental results with a thick ER fluid

It is understandable that in practical applications, the range of achievable damping by controlling the voltage applied to the damper is a very important factor. The larger the range is, the better the damper. This range is virtually defined by the area between the curves of zero voltage and maximum voltage.

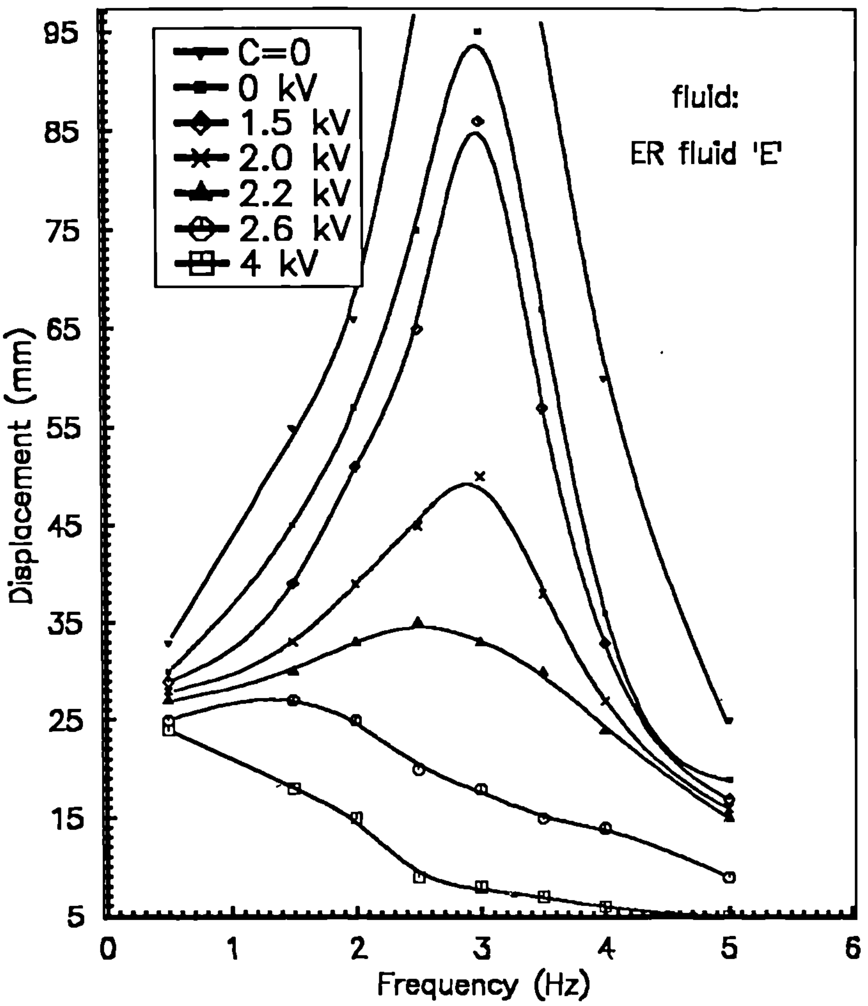

Figure 5.9: Experimental results with a thin ER fluid

To increase the range, it is necessary to reduce the original viscosity of the ER fluid or to increase the shear effect at maximum voltage. The ER fluid properties required for dampers are, it can be seen, actually the same as those for torque transmitting devices.

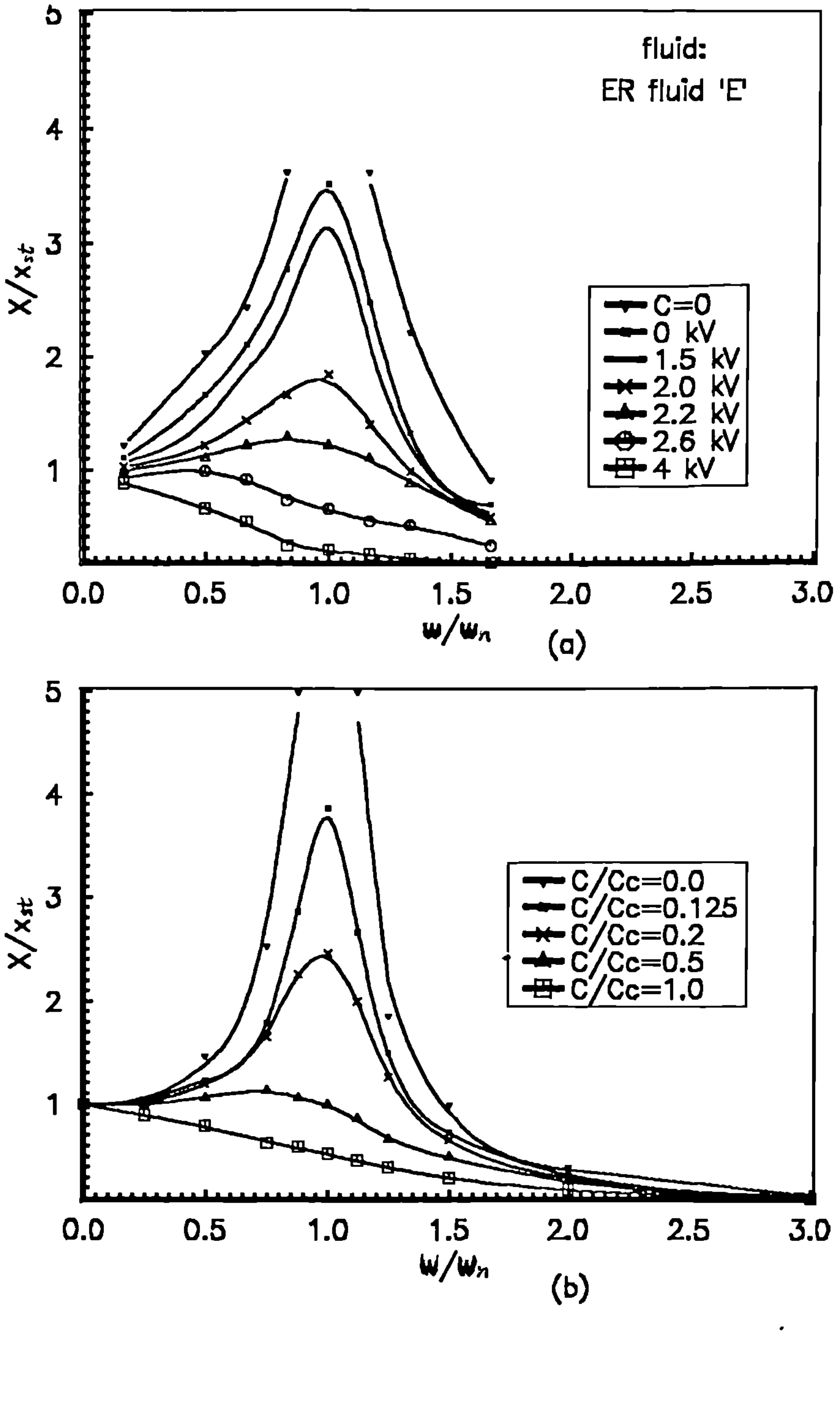

Figure 5.10: Comparison between conventional damper and ER damper

An alternative way to improve the range is to use an ER fluid with a lower mass ratio. However, the change of the configuration of an ER damper can also change its performance, as is clearly expressed in equation (5.4).

To determine the effectiveness of the ER damper, it is worthwhile to compare the results shown in Figure 5.9 with classical results. Figure 5.10a shows the results from fluid 'E', in which displacement is expressed in terms of the dynamic magnification ratio and frequency in terms of frequency ratio, whilst classical results [122] are shown in Figure 5.10b. It is clear that these results are surprisingly similar. However, it must be remembered that the classical Figure was produced by testing a variety of fluids with different viscosities, whilst the results with the ER damper were obtained by testing one ER fluid but varying the applied voltage. Significantly, the applied voltage is continuously variable. This means that an ER damper is equivalent to a number of classical dampers with fluids of different viscosity.

As implied by the unique characteristics of ER dampers, it is envisaged that an ER damper could be utilised as an adaptive damping element by incorporating a closed-loop control system.

5.7 Summary of Chapter 5

From the above theoretical and experimental analyses, the following conclusions can be drawn.

1. The damping performance of an ER damper is continuously variable by controlling the applied voltage.

2. It has been demonstrated that ER fluids of low mass ratio always behave viscously, no matter how large the electric field. Fluids of high mass ratio at high electric fields behave more like Coulomb damping than viscous damping, whilst at low fields the fluid behaves more like viscous damping.

3. It has been shown that fluids of low particle mass ratios (below 1:5, and thus of small unstressed viscosity) present a wider range of variability of damping performance than fluids of higher particle mass ratios (above 1:1).

4. If the ER damper is controlled as an open-loop system, i.e., by manual modulation of applied voltage, then it behaves like a kind of semi-active suspension device which could have potential applications in the modern toy industry, sports training facilities as well as vehicle engineering. It is very important to note that at a stage when adaptive suspension systems are either too expensive or not sophisticated enough for practical applications, many car companies are developing their semi-active suspension systems [114].

5. The most significant applications of ER dampers are to active suspension systems, such as on racing cars and military vehicles, which require closed-loop control. Compared with hydraulically controlled active suspension systems, the ER active suspension systems possess the advantages of simple configuration and easy control.

6. ER dampers have been shown to be more promising than other ER devices, such as ER power transmission (Chapter 3) and ER hydraulic control valves. It is predicted that ER dampers will probably be the first ER devices to be employed in practical applications.

CHAPTER 6

ELECTRORHEOLOGICAL CONTROL VALVES FOR HYDRAULIC SYSTEMS

6.1 Introduction

Hydraulic power has been used to advantage in various areas such as transportation, machine tools, industrial equipment, space technology, aircraft, and mining. The control of hydraulic power has been developed to a high degree in the last half century. A hydraulic circuit generally consists of a pump, controls for pressure level, direction and flow rate, together with a hydraulic cylinder or motor to provide linear or rotary force and motion. Although electronic technology has made hydraulic controls simpler and more reliable, the cost of production of the hydraulic equipment, particularly control valves, are still very high.

The development of ER technology provides a new opportunity in the design and manufacture of control valves. By employing an ER fluid in a hydraulic circuit, the mechanical movement, which occurs in conventional control valves, is no longer present.

The concept of an ER valve was first put forward by Winslow [17] and was further developed in the 1980's [97]. However no practical application of ER valves in a hydraulic circuit have been forthcoming. This is mainly due to the limited shear stress which the ER fluids can sustain. Fortunately, the ER effect has attracted the attentions of some major industries like chemical companies and automotive companies, and consequently better fluids are under development.

This Chapter will discuss the principle of the ER control valve as a pressure control valve, a direction control valve and a flow rate control valve. Advantages and disadvantages will also be discussed. Finally, the concept of a "universal ER control valve" is described and an application is presented.

6.2 The Principle of the ER Valve

For convenience of discussion and calculation, the dynamic viscosity μ is taken as the only parameter to describe the state of the ER fluid under the application of an electric field E. Suppose there is a laminar flow of an ER fluid in a rectangular passage of width b, height h and length L in the direction of flow, as shown in Figure 6.1. An electric field E transverse to the direction of flow is applied between the two surfaces which form height h. A pressure difference p is applied across the fluid in the passage. Then the force opposing motion is

$$F_o = -\mu \frac{dv}{dy} 2bL \tag{6.1}$$

and the force causing the motion is:

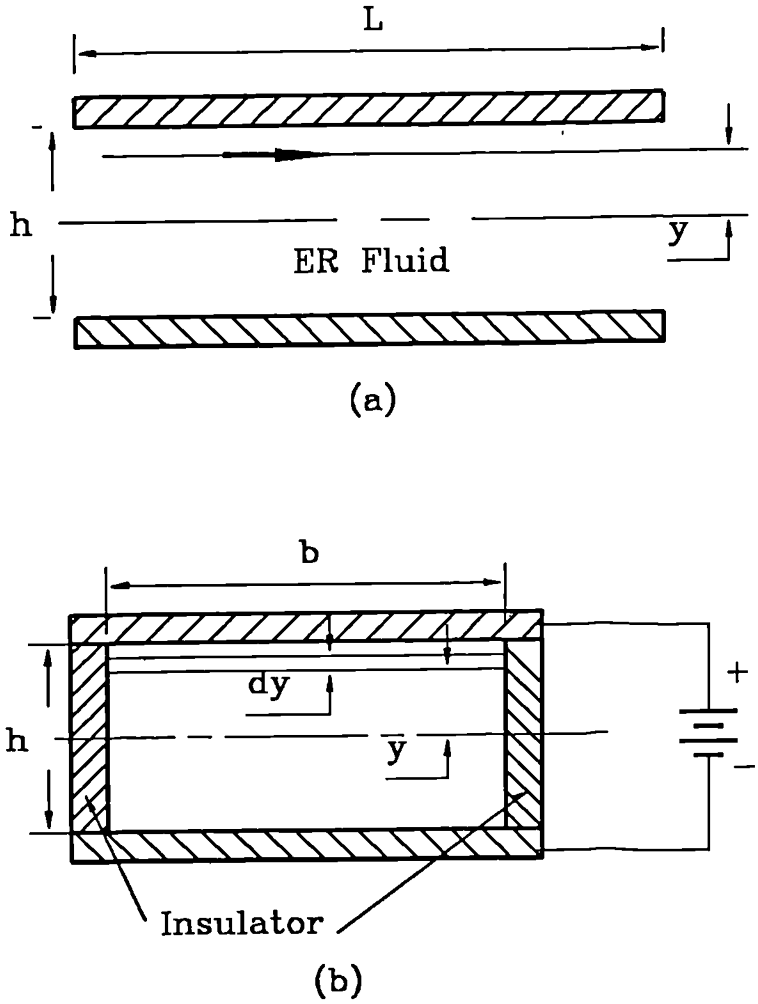

Figure 6.1: ER fluid flow in a unit valve

$$F_c = pbh. \tag{6.2}$$

There are two possible situations for the motion of the fluid:

1. When a high electric field is applied across the fluid, the apparent viscosity of the ER fluid becomes very large and the force opposing the motion is larger than that able to cause the motion, that is,

$$F_o > pbh \tag{6.3}$$

The larger the electric field applied to the fluid, the larger the pressure difference p needed to cause the motion. This is the case for an ER valve used as a directional control valve. Such valves are applied either with maximum electric field or with zero field.

2. When a relatively low or zero electric field is applied to the fluid, the viscous friction in the passage is not large enough to oppose the fluid motion. Dynamic equilibrium will be established in the passage, that is:

$$2pby = -\mu \frac{dv}{dy} 2bL \tag{6.4}$$

The solution of equation (6.4) will lead to a relationship between flow rate Q, pressure p and viscosity μ [120], that is:

$$Q = \frac{pbh^3}{12\mu L} \tag{6.5}$$

or

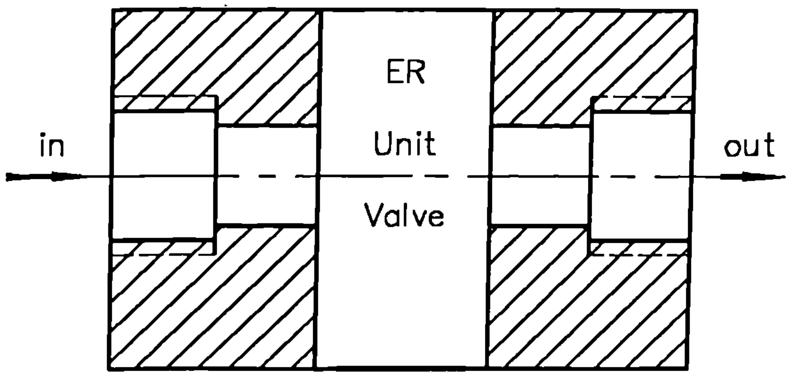

Figure 6.2: An ER two-way valve

worth mentioning that conventional valves (such as check valves) can also be used in an ER control system.

6.3.2 Two-way Valves

This is the simplest case of an ER valve. A two-way valve simply consists of a basic unit and two flow ports, as shown in Figure 6.2. The flow cannot pass between input and output ports until the electric field applied between the electrodes is reduced to a certain level.

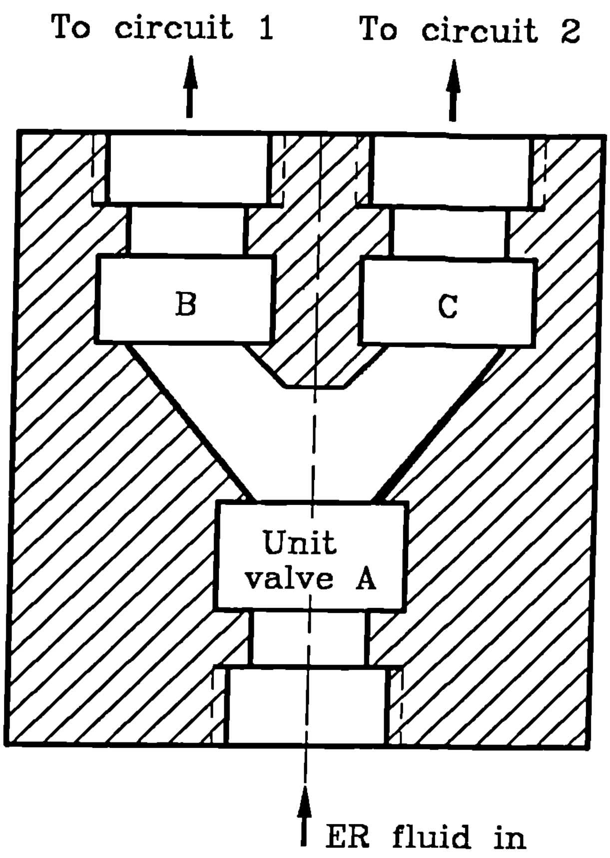

Figure 6.3: An ER three-way valve

6.3.3 Three-way Valves

Three unit valves are needed to form a three-way valve, as shown in Figure 6.3. When units A and B are discharged, the flow goes to circuit 1; when units A and C are discharged, the flow goes to circuit 2; and when all the units are discharged, the flow goes to two circuits.

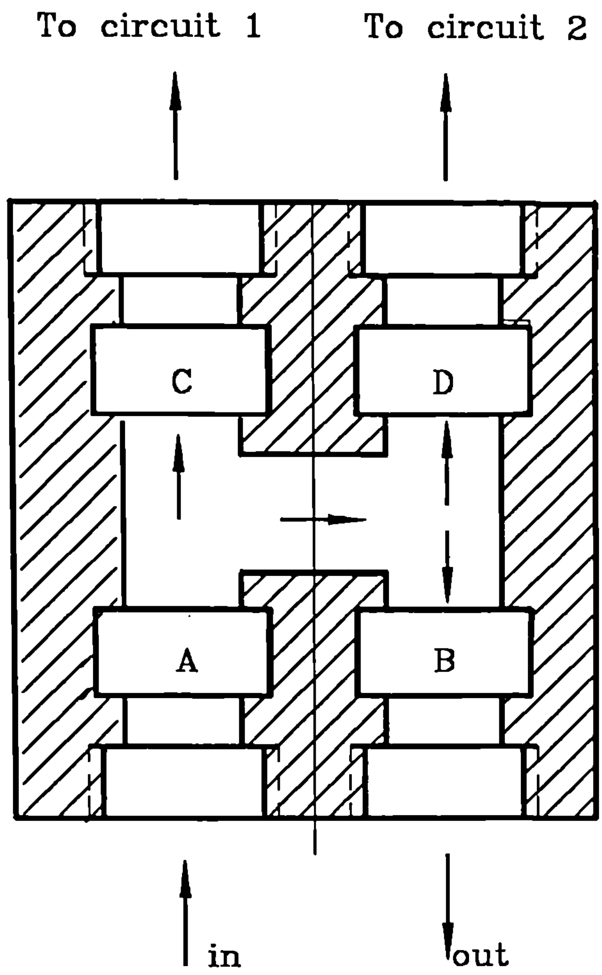

Figure 6.4: An ER valve consisting of four unit valves

6.3.4 Four-way Valves and Universal Control Valve

First of all, let us consider the situation when four unit valves are connected to each other, as shown in Figure 6.4. It is clear that the flow could be arranged to flow from one port to the others. This valve can be used as a two-way and a three-way valve. But when it is required that the pressurised liquid flows from C and B to a working cylinder and the outlet liquid flows back from A and D to an oil tank, then the flows would interfere. This implies that a four-way valve cannot be realised simply by the connection of four unit valves to form four ports.

To meet the four-way requirement, two layers of valves like those shown in Figure 6.4 have to be combined together, with a common earth electrode sandwiched in the middle of the eight unit valves. Thus the flows on each layer will not interfere with each other. This idea is shown in Figure 6.5. It can be seen that every port is connected with two unit valves, i.e., A1, A2 or B1, B2 or C1, C2 or D1, D2. Therefore, if either unit valve is discharged, the port will allow fluid to flow through. In this way, any kind of four-way valve is possible.

Table 6.1 shows a few examples of the functions of an ER four-way valve. It is clear that an ER four-way valve can also be used as a two-way and a three-way valve. Hence, a four-way ER control valve is indeed a universal directional control valve. More importantly, some of the by-pass ports leading to by-pass circuits can be arranged to be incorporated in the body of the universal four-way ER valve. As shown in Figure 6.6, ports E and F lead to two by-pass circuits. It is difficult for a conventional valve to incorporate such a by-pass valve.

It should be noted that there are various ways to arrange the positions of ports. Ports can either be arranged on the same side, as shown in Figure 6.7,

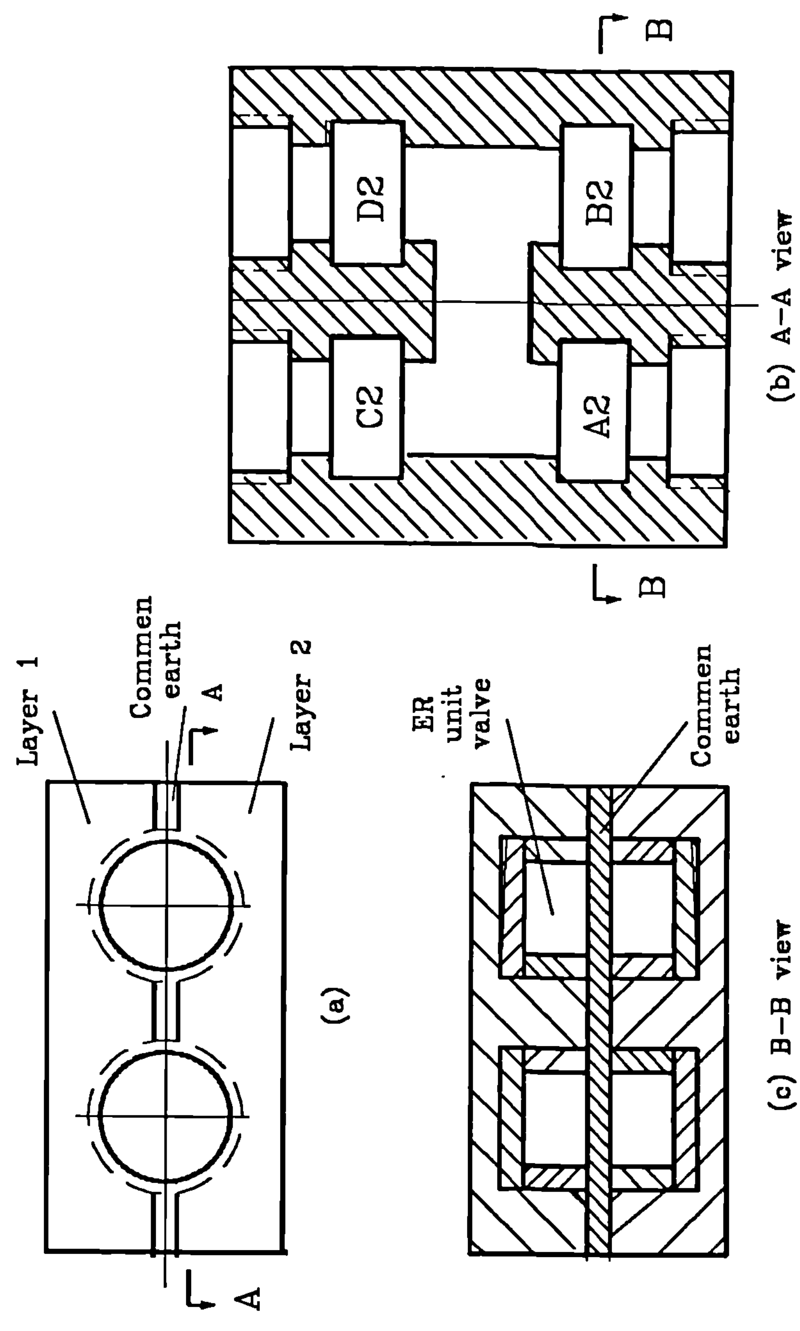

Figure 6.5: A universal ER directional control valve

(Normal Mode of Valve–Charged)

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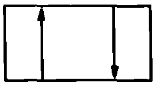
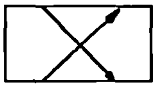
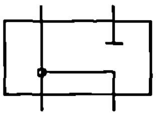
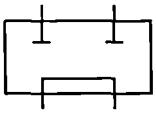
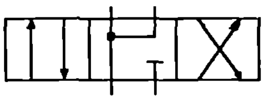
<tr><td></td><td>Discharge: A1C1, B2D2</td></tr>
<tr><td></td><td>Discharge: B1C1, A2D2</td></tr>
<tr><td></td><td>Discharge: A1C1D1 or A2C2D2</td></tr>
<tr><td></td><td>Discharge: C1D1 or C2D2</td></tr>
<tr><td>⋮</td><td>⋮</td></tr>
<tr><td></td><td>Discharge:<table><tr><td>A1C1B2D2</td><td>A1B1C1</td><td>B1C1A2D2</td></tr></table></td></tr>
<tr><td>⋮</td><td>⋮</td></tr>
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Table 6.1: Different functions achieved by an ER universal valve

or on a few sides of the valve body, as shown in Figure 6.6, according to the application requirement.

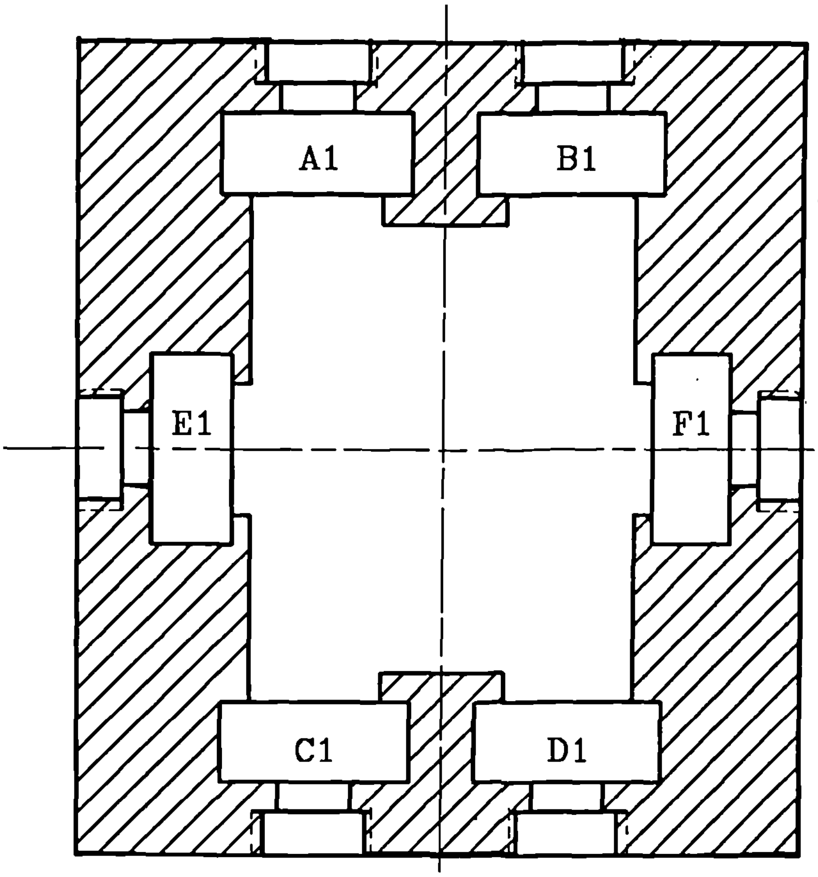

Figure 6.6: An ER directional control valve with two by-pass valves

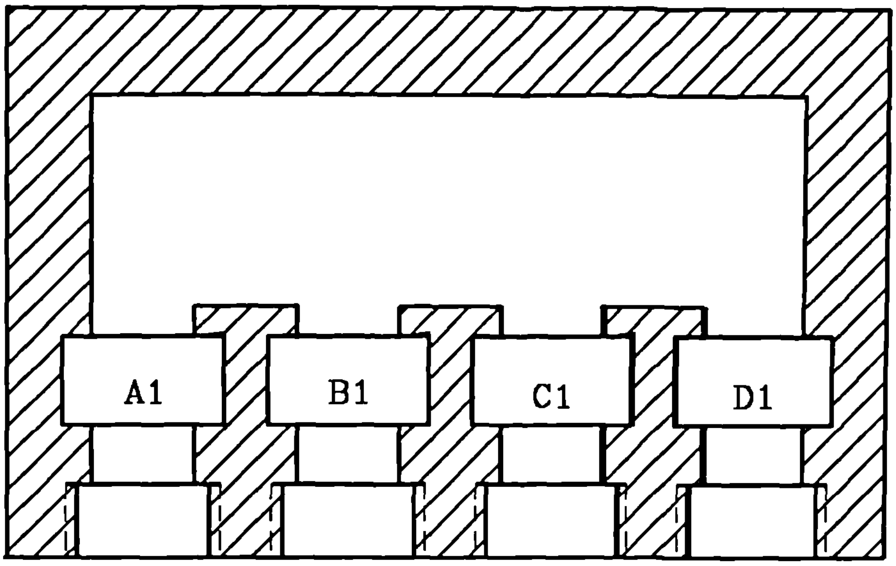

Figure 6.7: A universal ER directional control valve with all ports arranged on the same side

6.3.5 Multiple Flow Valves

By employing multiple unit valves, a multiple flow valve can be designed for use in hydraulic systems which have multiple circuits.

6.4 ER Pressure and Flow (Rate) Control Valves

For a given ER valve, it can be seen from equation (6.5) that once the flow rate Q is determined, the pressure difference p can be varied by changing the electric field applied across the ER valve, i.e. by changing the apparent viscosity of the ER fluid in the valve. The same applies to the control of flow rate once the pressure difference is determined. This is the principle of ER pressure and flow control valves.

Like ordinary fluids, the effective viscosity of the ER fluid varies with temperature and other factors, even when the electric field is constant. It is therefore difficult to control the pressure or flow rate accurately unless closed-loop control is provided. However it should be pointed out that conventional pressure and flow control valves can be used for the required functions in a hydraulic circuit using an ER fluid.

6.5 Example of an ER Control Valve in Application

Conventionally, the motion of a hydraulic cylinder is controlled by a four-way, two-position or three-position directional control valve. This is shown in Figure 6.8a. The functions of the valve can also be achieved by using an ER four-way valve as, shown schematically in Figure 6.8b. When the cylinder is required to move to the right, unit valves B1C1 and A2D2 are discharged; when the cylinder is required to move to the left, unit valves B1D1 and A2C2 are discharged.; When the cylinder is required to be stationary, A1B1 or A2B2 are discharged.

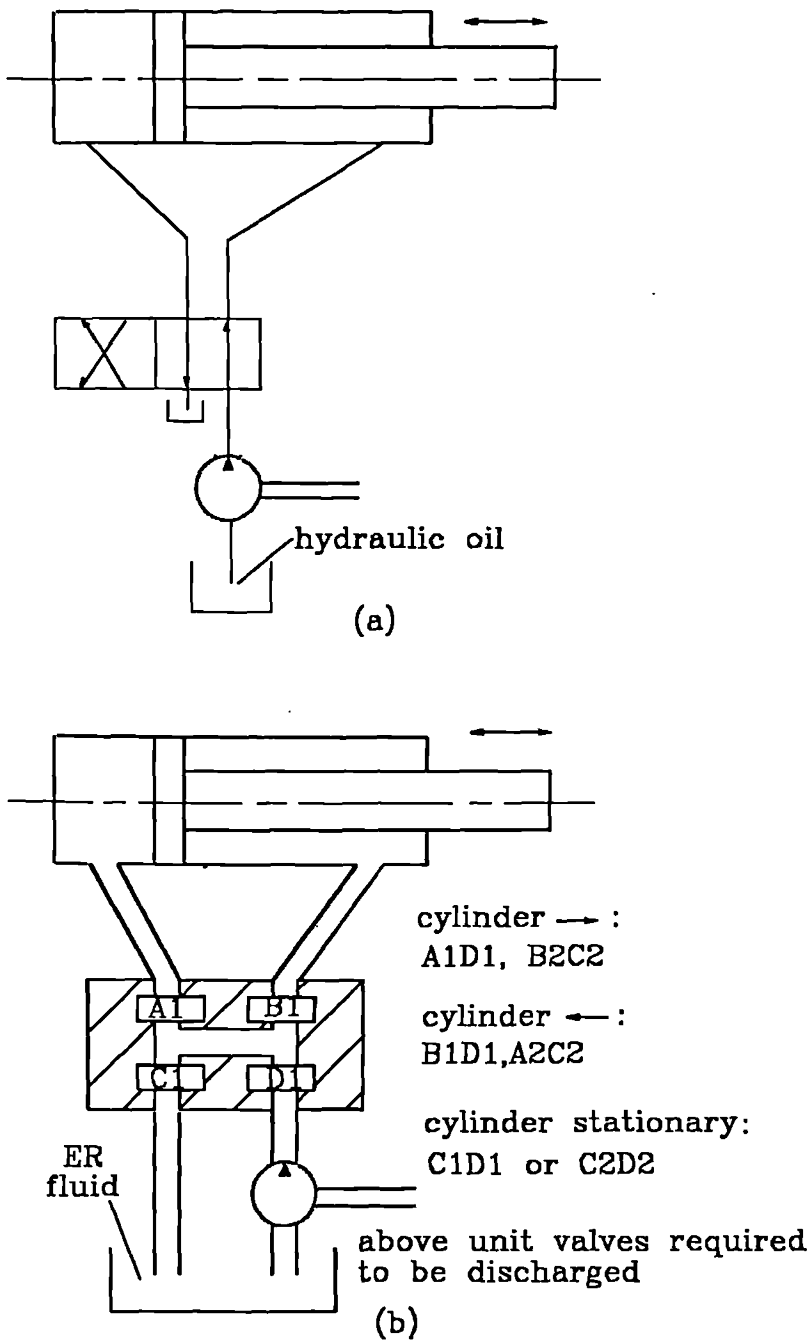

Figure 6.8: An example of an ER four-way valve controlling a hydraulic ram

6.6 Summary of Chapter 6

It has been shown in this Chapter that an ER valve is viable only when the liquid medium for the whole hydraulic system is an ER fluid. At present, ER fluids are more viscous than conventional hydraulic oils and this could be a problem for the pumping of the fluid. It is desirable that better and thinner ER fluids will be available in the future. Temperature instability will also affect the apparent viscosity of an ER fluid and thus the friction force opposing the motion will be affected.

The advantages of the ER valve over conventional valves are:

1. Low production costs because there are no moving parts in the valve.

2. Flexible port positions.

3. Simple construction.

4. Light-weight.

5. Potential short response time.

6. Easy control because all actions are control by electrical signals.

7. By pass circuits.

Their disadvantages are:

1. Temperature instability in pressure and flow control valves (directional control valves are not affected by temperature, because of their "on-off" property).

2. Large hydraulic systems require too much ER fluid. This influences the economy if the ER fluids are expensive.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1 General Conclusions

The preceding six chapters have presented theoretical and experimental analyses of the properties of ER fluids and their engineering applications. Results show that ER fluids exhibit a remarkable increase in apparent viscosity when subjected to an electric field. This kind of unique property can be used to conceive a series of applications like continuously variable power transmission devices, variable damping devices and hydraulic control valves. The following conclusions are therefore drawn:

1. The effectiveness of the ER effect is determined by the following factors: electric field strength and frequency applied to the ER fluid, current passing through the fluid, resistance and permittivity of the fluid, resistance of the circuit and temperature of the fluid. A change in any of these factors will lead to a change in the ER effect. It is indicated that the decrease in permittivity, field frequency, circuit resistance and the increase in fluid resistance generally benefit the ER effect. It is indicated that the length of ER response time is proportional to both circuit resistance and

fluid permittivity. Thus to achieve a fast responsive ER fluid, it is necessary to reduce the circuit resistance and fluid permittivity.

2. The ER power transmission devices have demonstrated that transmitted torque increases with applied voltage. The higher the voltage an ER fluid can sustain, the larger the torque that can be transmitted. A continuously variable output speed can be achieved simply by changing the voltage applied to the ER fluids.

3. Increases in the temperature of the ER fluid lead to a decrease in the pure viscous effect of the fluid but also to an increase in the pure electrorheological effect.

4. To be successfully applied in power transmission situations, improved ER fluids are required with improved electrically induced shear stresses and a lower unstressed viscosity.

5. Analysis show that an ER coupling has the disadvantage of low efficiency at low speed ratios. By integrating a mechanical gear train to work in conjunction with it, a large portion of power can be arranged to be transmitted through a high efficiency gear train, thus improving the efficiency of the whole system.

6. Results show that the performance of ER dampers is continuously variable by controlling the applied voltage. Therefore, an ER damper can be adopted to be used to develop an adaptive suspension system.

7. ER dampers have shown an more promising feasibility than other ER devices, such as ER power transmission and ER hydraulic control valves. It is predicted that ER dampers will probably be the first ER devices to be employed in practical applications.

8. ER fluids can be used to develop a series of hydraulic control valves which, compared with conventional valves, have the advantages of low production cost, simple construction, short response time and straightforward control.

9. The ER fluids used are not good enough and concentrated research on improving the ER fluid is needed.

7.2 Suggestions for Further Research

From the work reported in previous chapters, it can be seen that ER fluids need further development before widespread commercial applications become feasible. Although fluids with a 15 kPa induced shear stress are reported available [113,114], this figure still can not meet the requirements of power transmission. The shear stress of present ER fluids can be large enough for vibration absorber applications, but the temperature and storage stability of the fluid still remain as problems.

However, to find better fluids, it is important first of all to understand how different parameters influence the properties of the ER fluids. Some related theoretical analysis has been presented in Chapter 2 and some conclusions

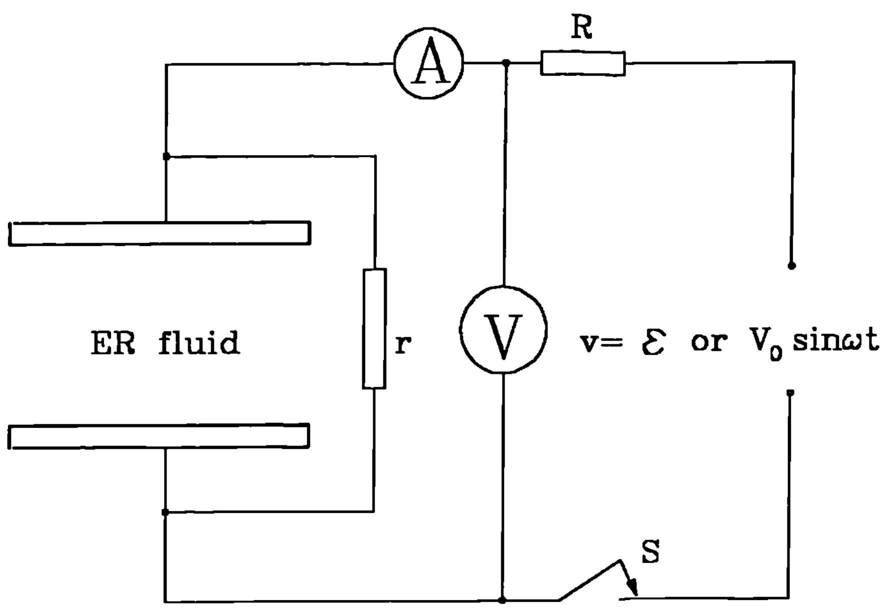

Figure 7.1: An ER model circuit

have been reached. However, no experimental work was carried out to prove the conclusions.

On the other hand, as temperature influences the stability of ER effect, it is important to understand the heat transfer properties of ER fluids.

It is essential that experiments should be done to investigate the performance of an adaptive suspension system using an ER damper as the active damping element.

Further considerations related to the construction of ER devices are also required.

These are suggested below as references for further research.

7.2.1 Parameters Influencing ER Effect

Preliminary theoretical analysis on parameters influencing the ER effect has been reported in Chapter 2. It was shown, for example, that the electric field strength applied to the ER fluid decreases with increasing circuit resistance, field frequency and system capacitance, but increases with fluid resistance. However, these analysis results are not verified by experimental results.

Figure 7.1 shows the suggested experimental method. For a given ER device and ER fluid, that is a given size of device, permittivity and resistance of the fluid, the current passing through and the voltage applied to the fluid are monitored. By changing the wave form and frequency of the electric field and circuit resistance of the system, the current and voltage will also be changed.

Comparing the experimental results with the theoretical results, a clear understanding of how different factors influence ER effect can be obtained. These results would be a valuable reference for research dedicated to improving the properties of ER fluids.

7.2.2 Thermal Conductivity of ER Fluid

The author performed some preliminary experiments to measure the thermal conductivity of ER fluids. For a various reasons, the results are not reliable and thus not included in the main body of this thesis. However, the method

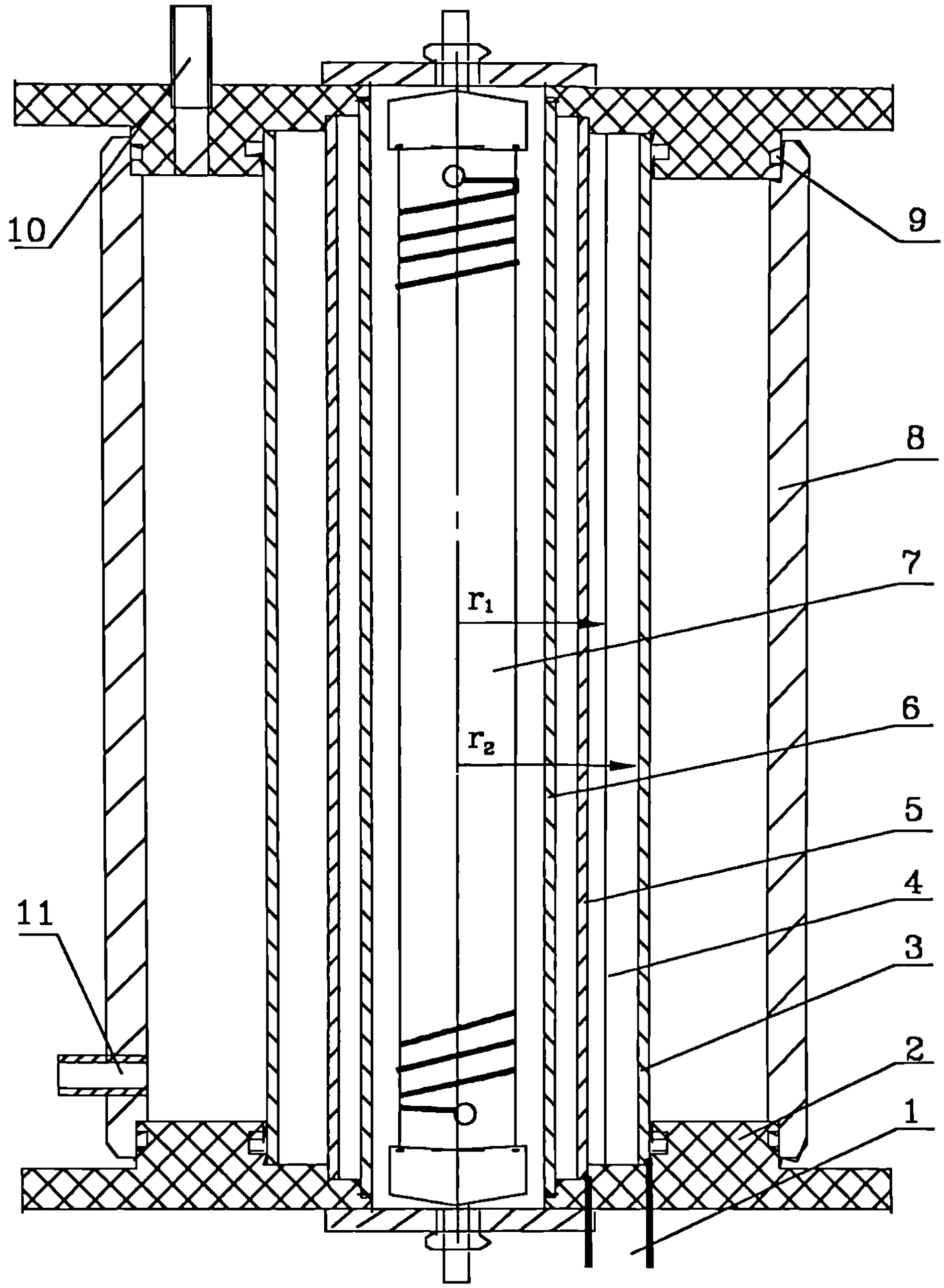

Figure 7.2: Thermal conductivity test rig for ER fluids
1.Electrode connections, 2.Insulator cover, 3.Outer tube, 4.Line
5.Live tube, 6.Protection tube, 7.Heating element, 8.Casing,
9.'O' ring seal, 10,11.Cooling water inlet and outlet.

and equipment is described below in the hope that it will provide some hints for further research on this topic.

It is known that the heat conduction normal to an isothermal surface is given by the Fourier equation:

$$\lambda = \frac{Q}{A\dfrac{\Delta t}{\delta}} \tag{7.1}$$

This equation applies to most fluids with the exception of liquid metals. To measure the thermal conductivity of ER fluids, the vertical coaxial cylindrical method was used [123]. Figure 7.2 shows the rig where (1) is an adjustable heat source, (3) and (4) are copper tubes used as the high voltage and the earth electrodes. The heat is removed by the circulating water between tubes (3) and (4). Temperatures t_1 and t_2 are respectively measured at the surfaces of r_1 and r_2 by connecting the wire of an electronic thermometer to them. As the wire could not be connected to the outer surface of the live tube, a linen line was arranged in the middle of the fluid for the connection of the wire measuring t_1. Equation (7.1) in the vertical coaxial cylinder case then yields

$$\lambda = \frac{Q \ln \dfrac{r_2}{r_1}}{2\pi l(t_1 - t_2)} \tag{7.2}$$

where Q is the heat conducted which is the energy produced by the heat source and l is the effective heat conducting length.

However it may not be accurate to measure r_1, r_2 and l, thus the equation is re-written as:

$$\lambda = \frac{CQ}{t_1 - t_2} \tag{7.3}$$

where C is a constant which is determined by measuring other liquids whose thermal conductivities are known. In this case, water, acetone, and air are used to decide the C.

This rig was calibrated within an accuracy of 5% without applying a high voltage.

To gain a comprehensive picture of the thermal conductivity of ER fluids, many samples were chosen: base oils (50 and 100cSt silicone oil) and ER fluids with different ratios of starch (dielectric particle) to base oil.

Unfortunately, there were three factors which affected the reliability of the test:

1. The application of the electric field affected the electronic thermometer.

2. The wire on the linen line would not maintain its position.

3. The gap between r_1 and r_2 is too small.

However, the results did show that the ER effect had very weak influence on the thermal conductivity of ER fluid. It is thought that the particle chains in ER fluids may help the heat conduction.

To improve the experimental procedure, the concept of the rig shown in figure 7.2 can be retained but the following improvements on the rig are suggested:

1. An non-electronic thermometer should be used to prevent the high electric field affecting electronic readings.

2. The gap between the two temperature radii should be larger in order to increase the temperature difference and thus reduce error.

3. The connections of thermometers should be more robust.

4. Thermal insulation at the two ends of the rig should be made more secure.

7.2.3 Testing of an Adaptive Suspension System

The ER technology will possibly be first applied in semi-active and active suspension systems. The properties of an ER damper has been studied in Chapter 5.

It is recommended that work be carried out on a single degree of freedom system such as that shown in figure 7.3. The displacement and acceleration are measured and compared with the reference value to produce a signal which is amplified and used to control the high voltage applied to the damper.

7.2.4 Construction Considerations for Future Design of ER devices

From our previous experience, it is strongly suggested that in the future design of ER devices, consideration be given to the selection of the gap size between electrodes. Sensitivity of the performance of the gap size is particularly

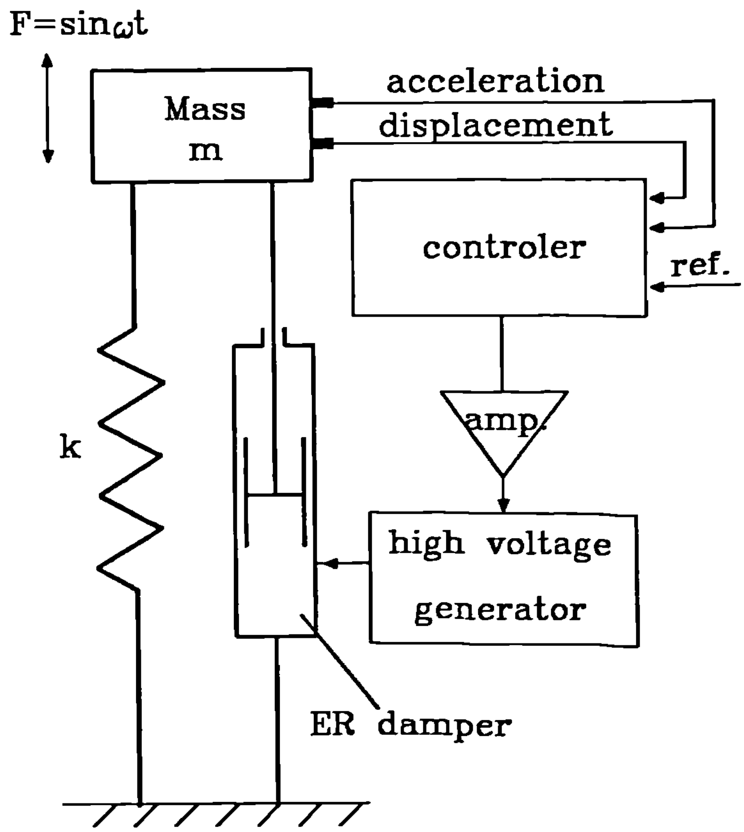

Figure 7.3: An active suspension system using ER damper

important. For example, in the multiplate drive shaft shown in figure 3.22, the intended gap is 2 mm. During the assembly, it was found that the gap between the first two plates was only 1.5 mm. Thus the adjacent gap was 2.5 mm. The different is 1 mm which means that when the fluid in one gap is fully stressed, the fluid in the adjacent gap is far from that stage. The error is actually $\frac{2.5-1.5}{2.0}=50\ \%$. However, if the designed gap is 4.0 mm, a 0.5 mm change in the gap only causes an error of 25%.

Due to a variety of reasons, the gap between electrodes may unavoidably change, and the best way to reduce the kind of error is to select a reasonably large gap. However, an increase in the gap will lead to an increase in the high voltage required. A compromise is needed in practice.

Appendix A: Compositions of ER Fluids Used in this Thesis

ER Fluid	Particle (mass ratio %)	Carrier (viscosity cSt)	unstressed viscosity (Ns/m^2)
'A'	Starch (50)	Silicone oil (50)	0.982 [88]
'B'	Starch (50)	Silicone oil (100)	1.427 [88]
'C'(ICI)	Starch (--)	Silicone oil (--)	--
'D'(ICI)	Starch (--)	Silicone oil (--)	--
'E'	Starch (16.7)	Silicone oil (10)	--
'F'	Starch (50)	Silicone oil (10)	--

Appendix B: Specifications of Equipment Used in this Thesis

Name	Model	Range
Brandenburg DC high VOLTAGE supply	2807R Alpha II Range	V=0 to 30 kV ±100 V, A=1 mA
Treck High Voltage Supply	Model 664	0 to 20 mA, 0 ± 11.0 kV (AC and DC)
AC High Voltage Supply	--	50 Hz, 0 to 5.o kV
Vibro-meter Dynamometer	2WB15	0 to 280 Nm, 0 to 10,000 rpm
Universal Avometer	Model VIII	current from 0.5 μA
DC Motor (I)	Neco	0.5 hp, 0 to 2,000 rpm
DC Motor (II)	Stromberg	22 kW
Sanderson Vibration Apparatus	(teaching equipment)	f=0 to 5.0 Hz
Comarck Electronic Thermometer	Model 1624	$-60°C$ to $170°C$ $\pm 0.5°C$
Optical Digital Speedometer	Compact 6000	0 to 10,000 ±1 rpm

Appendix C: Error Analysis

It was noted that there existed obvious errors with the experimental results. There were many factors which affected the data accuracy. First of all, systematic errors existed with torque and speed measurements. Although the system was calibrated, an uncertainty with torque digital expression was observed. Secondly, a variety of random errors were inevitable, such as temperature influence, data reading uncertainty and the fluctuation of the voltage applied to the drive shaft.

The error of torque measurement in section 3.4 is taken as an example for analysis. In this case, torque is the product of force F and the length of moment arm L, that is

$$T = FL$$

where $F = F_0 \pm 0.05 \quad (kg)$, L =0.25 m. Thus

$$T = 10(0.25F_0 \pm 0.25x0.05) \quad (Nm)$$

$$= 2.5F_0 \pm 0.125 \quad (Nm)$$

Thus the fractional error for a typical torque, 2.0 Nm, is

$$\frac{\Delta T}{T_0} = \frac{0.125}{2} = 6.4\ \%.$$

For the results in Figure 3.34, although torque and speed measurement are respectively to the accuracy of $\pm 0.1Nm$ and $\pm 1rpm$, the digital display of torque was somehow affected by the high electric field. Therefore, it is not reasonable to assume that torque measurement still has the accuracy of

$\pm 0.1Nm$. It is assumed that a $\pm 1.0Nm$ uncertainty was existed with this group of results.

REFERENCES

1. Jordon, T. C. and Shaw, M. T., 'Electrorheology', IEEE Transactions in Electrical Insulations, Vol. 24, No. 5, pp. 849-878 (1989)

2. Duclos, T.G., Acker, D.N., and Carlson, J.D., 'Fluids That Thicken Electrically', Machine Design, Jan. 21, 1988, pp43-46

3. Wakefield, C. C., 'Hydraulic Oils", London, (1960)

4. Zhu, J. C., Wei, C. G. and Zheng, M. Q., 'Vehicle Hydrodynamic Transmission', Book 1, Machinery Industry Press (China), (1982)

5. Liu, J.K., 'Development and Applications of Hydroviscous Drives', ASME, 74-DE-6, April, 1974

6. Konig, W., 'Bestimmung einiger Reibungscoefficienten und Versuche uber den Einfluss der Magnetisirung und Electrisirung auf die Reibung der Flussigkeiten', Ann. Phys. Lpz, Vol.25, pp.618-625 (1885)

7. Duff, A. W., 'The Viscosity of Polarised Dielectrics', Physical Review, Vol.4, No.1, pp.23-38 (1896)

8. Andrade, E.N. DA C., and Dodd, C., 'Effect of an Electric Field on the Viscosity of Liquids', Nature, Vol.143, p.26 (1939)

9. Sossinski, S., 'Effect of an Electric Field on the Viscosity of Liquids', Nature, Vol.144, p.117 (1939)

10. Andrade, E.N. DA C., and Dodd, C., 'Effect of an Electric Field on the Viscosity of Liquids', Nature, Vol.144, pp.117-118 (1939)

11. Andrade, E.N. DA C., and Dodd, C., 'The Effect of an Electric Field on the Viscosity of Liquids', Proc. Royal Society, A, Vol.187, pp.296-337 (1946)

12. Andrade, E.N. DA C., and Dodd, C., 'The Effect of an Electric Field on the Viscosity of Liquids II', Proc. Royal Society, A, Vol.204, pp.449-464 (1951)

13. Eisenschitz, R. and Cole, G. H. A., 'Theory of the Effect of an Electric Field on Liquid Viscosity', Phil. Magazine, Vol. 45, pp. 394-400 (1954)

14. Bjornslahl, Y., 'The Influence of an Electric Field on the Viscosity of Aeototropic Liquids', Physics, Vol.6, No.8, pp.257-264 (1935)

15. Bjornslahl, Y. and Snellman, K. O., 'The influence of an Electric Field on the Viscosity of Pure Liquids and Colloidal Suspensions', Kolloid Zeit, Vol.78, No.3, pp.258-272 (1937)

16. Bjornslahl, Y. and Snellman, . O., 'Viscosity of isotropic Liquids in an Electric Field', Kolloid Zeit, Vol.86, No.2, pp.223-230 (1939)

17. Winslow, W. M., 'Induced Fibration of Suspensions', J. of Applied Physics, Vol.20, pp.1137-1140 (1949)

18. Winslow, W. M., 'Method and Means for Translating Electrical Impulses into Mechanical Force', U.S. Patent Specification No. 2,417,850 (1947)

19. Winslow, W. M., 'Field Controlled Hydraulic Devices', U.S. Patent Specification No. 2,661,596 (1953)

20. Winslow, W. M., 'High Fidelity Slip Control', U.S. Patent Specification No. 2,661,825 (1953)

21. Winslow, W. M., 'Field Responsive Force Transmitting Compositions', U.S. Patent Specification No. 3,047,507 (1962)

22. Klass, D. L. and Martinek, T. W., 'Electroviscous Fluids. I. Rheological Properties', J. of Applied Physics, Vol.38, No.1, pp.67-74 (1966)

23. Klass, D. L. and Martinek, T. W., 'Electroviscous Fluids. II. Electrical Properties', J. of Applied Physics, Vol.38, No.1, pp.75-80 (1966)

24. Klass, D. L. and Martinek, T. W., 'Electric Viscous Field Responsive Shock Absorber', U.S. Patent Specification No. 3,207,269, (1965)

25. Klass, D. L. and Martinek, T. W. and Brozowski, V., 'Electric Field Responsive Fluid and method of Preparation', British Patent Specification No. 1,076,754, (1967)

26. Martinek, T. W. and Klass, D. L., 'Electric-field-responsive Compositions', U.S. Patent Specification No. 3,412,031, (1968)

27. Martinek, T. W., 'Electroviscous Fluid Composition', U.S. Patent Specification No. 3,397,147, (1968)

28. Klass, D. L. and Brozowski, V., 'Electroviscous Fluid and Method of Using Same', U.S. Patent Specification No. 3,385,793, (1968)

29. Strandrud, H. T., 'Electric field valves inside Cylinder Control Vibrator', Hydraulic and Pneumatic, Vol.19, pp.139-143 (1966)

30. British Technology Group Report, Issue No. 1, 1987-1988

31. Bullough, W. A. and Stringer, J. D., 'The Utilisation of the Electroviscous Effect in a Fluid Power System', 3rd Int. Fluid Power Symposium, 9th-11th May, 1973, Turin, Italy

32. Bullough, W. A. and Stringer, J. D., 'Direct Flow Control by Electric Fields', Hydraulic & Air Engineering, Vol.5, No.4, pp.11-17 (1977)

33. Bullough, W. A. and Foxon, M. B., 'A Proportionate Coulomb and Viscously Damped Isolation System', Jour. Sound and Vibration, Vol.56, No.1, pp.35-44 (1977) (1977)

34. Stangroom, J. E., 'Improvements in or Relating to Electric Field Responsive Fluids', British Patent Specification No. 1,501,635 (1978)

35. Stangroom, J. E., 'Improvements in or Relating to Apparatus For the Controlled Hydration of Solids', British Patent Specification No. 1,534,170 (1978)

36. Stangroom, J. E., 'Improvements in or Relating to Electric Field Responsive Fluids', British Patent Specification No. 1,570,234 (1980)

37. Gerrish, A., 'Improvements in or Relating to Means for Damping Resilient Members', British Patent Specification No. 1,259,820 (1972)

38. Gerrish, A., 'Improvements in or Relating to Dampers', British Patent Specification No. 1,282,568 (1972)

39. Gerrish, A., 'Electro Viscous Vibrators', British Patent Specification No. 1,433,617 (1976)

40. Gerrish, A., 'Pile Driving Apparatus', British Patent Specification No. 1,511,648 (1976)

41. Okagawa, A., Cox, R. G. and Mason, S. G., 'Particle Behavior in Shear and Electric Field VI. The Microrheology of Rigid Spheroids', J. Colloid and Interface Science, Vol. 47, No. 2, pp.536-567 (1974)

42. Kimura, O., 'Studies on the Effect of Electric Field on the Viscosity of Liquids', Bull. Chemical Soc. of Japan, Vol.12, p.147 (1937)

43. Kimura, O., 'Studies on the Effect of Electric Field on the Viscosity of Liquids', Bull. Chemical Soc. of Japan, Vol.14, pp.243-249 (1939)

44. Uejima, H., 'Dielectric Mechanism and Rheological Properties of Electro-Fluids', Japanese Journal of Applied Physics, Vol.11, No.3 pp.319-326 (1972)

45. Honda, T. and Sasada, T., 'The Mechanism of Electroviscosity. I. Electrohydrodynamic Effect on Polar Liquids', Japanese Journal of Applied Physics, Vol.16, No.10, pp.1775-1783 (1977)

46. Honda, T. and Sasada, T., 'The Mechanism of Electroviscosity. II. Conductivity Effect of Dielectric Liquids on Electroviscosity', Japanese Journal of Applied Physics, Vol.16, No.10, pp.1785-1791 (1977)

47. Honda, T. and Sasada, T., 'A.C. Characteristics of the Electroviscous Effect', Japanese Journal of Applied Physics, Vol.19, No.8, pp.1463-1466 (1977)

48. Fukuzawa, K., Iguchi, M., Kumeoka, Y. and Taketani, T., 'Braking Action of Electroviscous Fluid between Rotating Disk and Stationary Disk', J. Mech. Eng. Lab. Japan, Vol. 29, No. 5, pp. 189-194 (1975)

49. Fukuzawa, K., Iguchi, M., Kumeoka, Y. and Taketani, T., 'On the Flow of an Electroviscous Fluid between a Rotating and a Stationary cylinder', J. Mech. Eng. Lab. Japan, Vol. 28, No. 4, pp. 189-194 (1975)

50. Sugimoto, N., 'Winslow Effect in Ionic Exchange Resin Dispersion', Bulletin of the JSME, Vol. 20, No. 149, pp. 1476-1483 (1977)

51. Shor, G. I., Lapin, V. P., Shkolnikov, V. M. and Likhterov, S. D., 'Electroviscous Effects in Lubricating Oils', Proc. J.S.L.E., ASLE Int. Lubrication Conference, Tokyo, July, 1975, pp. 623-630

52. Deinega, Y. F., Popko, K. K. and Kovganich, N. Y., 'The Role of Bound Water in the Electro-rheological Effect', Dopov. Akad. Nauk. Ukr. RSR, Ser. B, No. 9, pp. 807-810 (1975), (Royal Aircraft Establishment, Library Translation 2090, 1982)

53. Shul'man, Z. P., Matsepuro, A. D. and Khusid, B. M, Structure Formation in Electro-rheological Suspensions in an Electrical Field I. Qualitative Considerations', Vestsi Akademii Navuk Belaruskai SSR No. 3, pp. 116-121 (1977), (Royal Aircraft Establishment, Library Translation 2088, 1982)

54. Shul'man, Z. P., Khusid, B. M and Matsepuro, A. D., 'Structure Formation in Electro-rheological Suspensions in an Electrical Field II. Quantitative Evaluations', Vestsi Akademii Navuk Belaruskai SSR No. 3, pp. 122-127 (1977), (Royal Aircraft Establishment, Library Translation 2089, 1982)

55. Gorodkin, R. G., Korobko, Y. V., Blokh, G. M., Gleb, V. K., Sidorova, G. I. and Ragotner, M. M., 'Applications of the Electrorheological Effect in Engineering Practice', Fluid Mechanics--Soviet Research, Vol. 8, No. 4, pp. 48-61 (1979)

56. Arguelles, J., Martin, H. R. and Pick, R. J., 'Some Experiments with Electrosensitive Fluids', 3rd Int. Fluid Power Symposium, 9th-11th, May, 1973, Turin, pp. F2-25-35

57. Arguelles, J., Martin, H. R. and Pick, R. J., 'A Theoretical Model For Steady Electroviscous Flow Between Parallel Plates', Journal of Mechanical Engineering Science, Vol. 16, No. 4, pp. 232-239

58. Westhaver, J. W., 'Electroviscous Fluid', US Patent Specification No. 3,970,573 (1976)

59. Atten P. and Honda T., 'The electroviscous Effect and Its Explanation I- The Electrohydrodynamic Origin; Study under Unipolar D.C. Injection, Journal of Electrostatics, Vol. 11, pp. 225-245 (1982)

60. Arp, P. A., Foister, R. T. and Mason, S. G., 'Some Electrohydrodynamic Effect in Fluid Dispersions', Advances in Colloid and Interface Science, Vol. 12, No. 4, pp. 295-256 (1980)

61. Stangroom, J. E., 'Electrorheological Fluids', Phys. Technol., Vol. 14, pp.290-296 (1983)

62. Stangroom, J. E., 'The Electro-osmotic Theory of Electro-rheological Fluids', IEE Colloquium on Electrically Active Fluids, London, 13, Feb., 1985, pp. 5.1-5.2

63. Stangroom, J. E., 'Electro-rheological Fluids and Their Applications', Proc. of the Conf. on Materials Engineering, ME!, Leeds, England, 10-12, July, 1984, pp. 81-85

64. Block, H., Goodwin, K. M. W., Gregson, E. M. and Walker, S. M., 'Stimulated Resonance between Electric and Shear Fields by a Colloid System', Nature, Vol. 275, pp. 632-634 (1978)

65. Block, H., Goodwin, K. M. W., Qin, A., Tsangaris, G. and Walker, S. M., 'A couette Cell with Fixed Stator Alignment for the measurement of Flow Modified Permittivity and Electroviscosity', J. Phys. E. Sci. Instrum., Vol. 16, pp.896-902 (1983)

66. Block, H., Kluk, E., McConnell, J., and Scaife, B. K. P., 'Polarisation in Rotating Dielectrics', J. Colloid and Interface Science, Vol. 101, No. 2, pp. 320-329 (1984)

67. Block. H. and Kelly, J. P., 'Dielectric Properties of Fluids and Their Relation to Electrorheology', IEE Colloquium on Electrically Active Fluids, pp. 1-11-13, 13th of Feb., 1985

68. Block, H. and Kelly, J. P., 'Electrorheological Fluids', UK Patent GB 2,170,510 A, 6th of Aug., 1986

69. Gorodkin, R. G., Glokh, G. M., Bukovich, I. V. and Demidenko, T. A., 'The Flow of an Eelectrorheological Suspension in Cells of Different Geometries', Elektroreol. Issled. i Pril. Minsk. pp. 52-65 (1981), (Royal Aircraft Establishment, Library Translation 2111, 1983)

70. Shul'man, Z. P. and Matsepuro, A. D., 'The Nature of Charge Carriers in Electrorheological Suspensions', Teplo Massoperenos: Teor. Prakt Prilozh., pp. 19-21 (1983), (Royal Aircraft Establishment, Library Translation 2137, 1985)

71. Stevens, N. G., Sproston, J. L. and Stanway, R., 'The Influence of Pulsed D.C. Input Signals on Electrorheological Fluids', Journal of Electrostatics, Vol. 17, pp. 181-191 (1984)

72. Stevens, N. G., Sproston, J. L. and Stanway, R., 'On the Mechanical Properties of Electro-rheological Fluids', Journal of Applied Mechanics, ASME Transactions, Vol. 54, No. 2, pp. 456-458 (1987)

73. Jordon, T. C., Wong, W. and Shaw, M. T., 'Rheo-optical and Materials Approach to Electrorheology', Annual Report-Conference on Electrical Insulation and Dielectric Phenomena-1988, Ottawa, Canada, 16-20, Oct., 1988, pp. 493-499

74. Femenko, E. B., Kovganich, N. Y. and Deinega, Y. F., 'Electrorheological and Dielectric Study of Ferrite Suspensions in Hydrocarbons', Sov. Surf. Eng. Appl. Electrochem., No. 1, pp. 52-55 (1985)

75. Peel, D. J., Firoozian, R. and Bullough, W. A., 'Derivation of the Electrical Characteristics of an Electro-rheological Fluid From Biased Sine Wave Excitation Tests', Proc. of 8th Int. Symp. on Fluid Power, Birmingham, England, 19-21, April, 1988, pp. 527-545

76. Firoozian, R., Bullough, W. A. and Peel, D. J., 'Time Domain Modelling of the Response of an Electro-rheological Fluid in the Flow Mode', ASME, Design Engineering Division (Publ) DE v 18-4. Pulb. by ASME, New York, pp. 45-50 (1989)

77. Lingard, S. Bullough, W. A. and Shek, W. M., 'Tribological Performance of an Electro-rheological Fluid', Journal of Physics D: Applied Thysics, Vol. 22 No. 11, pp. 1639-1645 (1989)

78. Sproston, J. L., Stanway, R. and Page, I. M., 'An Investigation of Torque Transmission Using Electrically Stressed Dielectric Fluids', Proc. of the 6th Conf. on Electrostatic Phenomena, Oxford, England, 13-15, April, 1983, pp. 53-58

79. Sproston, J. L., Stevens, N. G., 'Experimental Study of Electrorhelogical Torque Transmission', IEE Colloquium on Electrically Active Fluids, London, 13, Feb., 1985, pp. 2.1-2.4

80. Stevens, N. G., Sproston, J. L. and Stanway, R., 'Experimental Study of Electro-rhelogical Torque Transmission', Journal of Mechanics, Transmission, and Automation in Design, Vol. 110, No. 2, pp. 182-188 (1988)

81. Wu, X. M., Stanway, R. and Sproston, J. L, 'Electrorheological Fluids and Their Applications in Power Transmission and Active Suspension', Proc. of 22nd Int. Symp. on Automotive Technology and Automation, Florence, Italy, 14-18, May, 1990, pp. 823-830

82. Shullman, Z. P., Khusid, B. M., Korobko, E. V. and Khizhinsky, E. P., 'Damping of Mechanical-systems Oscilations by a Non-newtonian Fluid with Electric-field Dependent Parameters', Journal of Non-Newtonian Fluid Mechanics, Vol. 25 pp329-346 (1987)

83. Anaskin, I. F., Gleb, V. K., Korobko, E. V., Khizhinskii, B. P. and Khusid, B. M., 'Effect of External Electric Field on Amplitude-Frequency Characteristics of Electrorheological Damper', Journal of Engineering Physics (English Translation of Inzhenerno-Fizicheskii Zhurnal) Vol. 46, No. 2, pp. 233-238 (1984)

84. Stevens, N. G., Sproston, J. L. and Stanway, R, 'Experimental Evaluation of a Simple Electroviscous Damper', Journal of Electrostatics, Vol. 15, pp. 275-283 (1984)

85. Stanway, R., Sproston, J. L. and Stevens, N. G., 'Non-linear Modelling of an Electro-rheological Vibration Damper', Journal of Electrostatics, Vol. 20, pp. 167-184 (1987)

86. Stanway, R., Sproston, J. L. and Firoozian, R., 'Identification of the Damping Law of an Electro-rheological Fluid', ASME Paper No. 86-WA/DSC-6 (1986)

87. Stanway, R., Sproston, J. L. and Wu, X. M, 'Variable Suspension Damping Using Electrorheological Fluids', 2nd Int. Conf. on New Developments in Powertrain and Chassis Engineering, Strasbourg, France, 14-16, June, 1989, pp. 547-558

88. Stevens, N. G., 'Electrorheological Fluids and Their Engineering Applications', Ph.D. Thesis, Liverpool University (1985)

89. Choi, S. B., Gandhi, M. V. and Thompson, B. S., "Active Vibration Tuning Methodology for Smart Flexible Structures Incorporating Electro-rheological Fluids: A Proof-of-Concept Investigation', Proc. of the 1989 American Control Conference, Pittsburgh, PA, USA, 21-23, June, 1989, pp. 694-699

90. Choi, S. B., Gandhi, M. V. and Thompson, B. S., "Smart Structures incorporating Electro-rheological Fluids for Vibration-Control and Active-Damping Applications: An experimental investigation', ASME, Design Engineering Division (Publication) DE V 18-2. Publ by ASME, New York, pp. 229-236 (1989)

91. Gandhi, M. V., Thompson, B. S. and Choi, S. B., 'A Proof-of-Concept Experimental Investigation of a Slide-crank Mechanism Featuring a Smart Dynamically Tunable Connecting Rod Incorporating Embedded Electro-rheological Fluid Domains', Journal of Sound and Vibration, Vol. 134, No. 2, pp. 1-5 (1989)

92. Stangroom, J. E., 'Pipework Snubbers Based on Electro-rheological Fliuds', Proc. of Pipework Design and Operation, London, 19-20, Feb., 1985, pp. 279-284

93. Kenaley, G. L. and Cutkosky, M. R., 'Electrorheological Fluid-Based Robotic Fingers With Tactile Sensing', IEEE Int. Conf. Rob. Autom. 1989 v 1 (of 3), Pulb. by IEEE, Piscataway, NJ, USA, pp. 132-136 (1989)

94. Gandhi, M. V., Thompson, B. S., Choi, S. B. and Shakir, S., 'Electro-rheologivcal-fluid-based Articulating Robotic Systems', Journal of Mechanics, Transmissions, and Automation in Design, Vol. 111, No. 3, pp. 328-338 (1989)

95. Brooks, D. A. 'Electro-rheological Devices Provide Hydraulic/Electronic Interface', Design Eng. (GB), Nov., 1982, pp. 41-49

96. Brooks, D. A., 'Electro-rheological Effect Adds Muscle', Control and Instrum. (GB), Vol. 14, No. 10, pp. 57-59 (1982)

97. Brooks, D. A., 'Electro-rheological Devices', Chart. Mech. Engr., Vol. 29, No. 9, pp. 91-93 (1982)

98. Brooks, D. A., 'Fluids Get Tough', Phys. World (UK), Vol. 2, No. 8, pp. 35-38 (1989)

99. Gandhi, M. V., Thompson, B. S. and Choi, S. B., 'A New Generation of Innovative Ultra-Advanced Intelligent Composite Materials Featuring Electro-Rheological Fluids: An Experimental Investigation', Journal of Composite Materials, Vol. 23, pp. 1231-1255 (1989)

100. Gandhi, M. V., Thompson, B. S. and Choi, S. B., 'Ultra-Advanced Materials Incorporating Electro-Rheological Fluids', Proc. of the 4th Japan-U.S. Conference on Composite Materials, Washington, D.C., 27-29, June, 1988, pp. 875-884

101. Proceedings of the International Symposium on Electrorheological Fluids, Boston, USA, 4th of Aug., 1987

102. Proceedings of the 2nd International Conf. on Electro-rheological Fluids, Raleigh, North Carolina, USA, 7-9, Aug., 1989, Published by Technomic Publishing Company Inc..

103. Block, H. and Kelly, J. P. 'Electro-rheology', J. Phys. D: Appl. Phys., Vol. 21, pp. 1661-1677 (1988)

104. Webb, N. 'Electrorheological Fluids', Chemistry in Britain, April, 1990, pp. 338-340

105. 'Smart Fluids: New Route to Advanced Hydraulic Systems/Devices', Published by Technical Insights Inc. (1988)

106. 'ER Fluids', Chemistry in Britain, March, 1989, p. 241

107. Qin, A., 'Physico-chemical Studies of Macromolecular Systems in Solusions', Ph.D. Thesis, Liverpool University (1982)

108. Kelly, J. P., 'Studies in Electrorheology', M.Sc. Thesis, Liverpool University (1985)

109. Winch, R. P., 'Electricity and Magnetism', Published by Prentice-Hall Inc., New York (1955)

110. Chow, J. W. C., 'An Experimental Study of an Electrorheological Device for Torque Transmission', Final Year Project Report, Liverpool University (1988)

111. Pierce, S.M. and Shepherd, M. Development of a Modulating Viscous Fan Drive for Agricultural Tractors, SAE Spec. Publ. 524, Heavy Duty Engine Cool system in off-highway Meet. & Expo. Sep. 1982, USA

112. Douglas, J. F., Gasiorek, J. M. and Swaffield, J. A. 'Fluid Mechanics', Published by Pitman Publishing Ltd., London (1979)

113. Bullough, W. A and Peel D. J., 'Progress Towards a Hydraulic Semiconductor for Vehicle Application', Society of Automotive Engineers, Paper No. 0148-7191/88/1031-1786 (1988)

114. 'Electro-Rheological Fluids', American Cyanamid Company, Report No. NBD-001-86-2507

115. Bastow, D. 'Car Suspension and Handling', Pentech Press, 1980

116. Charalabbous, C., Brunning, A. and Crawford, I.L. 'The design and advanced development of a semi-active suspension', Proc. of 2nd EAEC Int. Conference on New Developments in Powertrain and Chassis Eng., Strasbourgh, France, 14-16, June, 1989 pp. 539-546

117. Active Suspension: Making It Happen , Automotive Engineer, Feb. 1989, pp. 60-61

118. Thompsion, A.G. 'Design of Active Suspensions', Proc. Instn. Mech. Eng., Vol. 185 36/71, pp. 553-563 (1971)

119. Ruzicha, J.E. and Derby, T.F. 'Influence of Damping in Vibration Isolation', Published by Shock and Vibration Information Center, United States Department of Defence, Washington (1971)

120. Douglas, J. F. 'Solutions of Problems in Fluid Mechanics', Published by Pitman Publishing Ltd., London (1975)

121. Hunt, J.B. 'Dynamic Vibration Absorber', Mech. Eng. Publications Ltd. London (1979)

122. Den Hartog, J.P. 'Mechanical Vibration', Fourth Edition, Published by McGraw-Hill Book Company (1956)

123. N.V. Tsederberg 'Thermal Conductivity of Gases and Liquids', Published by Edward Arnold (Publishers) Ltd., London (1965)